Photonics

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Semiconductor light sources – Part A

Optical properties of semiconductors

Semiconductor materials in photonics

- Semiconductor materials form the basis for:
  - Light emitting diodes (LED)
  - Diode lasers
  - Optical detectors and Solar cells

- Semiconductor materials:

  devices for efficient conversion from electricity to light and vice – versa.

- Semiconductor energy level structure:

  different from atoms, ions / molecules - Discrete levels

  → crystalline solid state: high number of discrete levels - wide energy range
  - Difference in achieving population inversion - pumping mechanism.

Content

- (Part A) Semiconductor materials
  - Energy level structure
  - Electrons and hole distribution over the energy levels
  - Optical gain, loss, refractive index
- (Part B) Role of pn-junctions and heterojunctions
- (Part C) Semiconductor light sources: Light emitting diode
- (Part D) Semiconductor light sources: Laser diode

Concepts semiconductor physics and devices

Assumption you know from: 5ECB0 Electronic circuits 1

Concepts assumed known:
- Electrons and holes
- Intrinsic and doped semiconductors
- Donor and acceptor concentration
- Electron and hole mobility
- Electron and hole diffusion

Concepts assumed to be new in this course:
- Bandgap
- Valence and conduction band
- Electron and hole recombination
- Electron and hole lifetime
- Direct and indirect bandgap
- Effective mass of electrons and holes
- Density of states
- Fermi level

In detail:
5XPB0 “Nanodevices and integration” B Q4
5CCA0 “Semiconductor physics and materials” M Q1

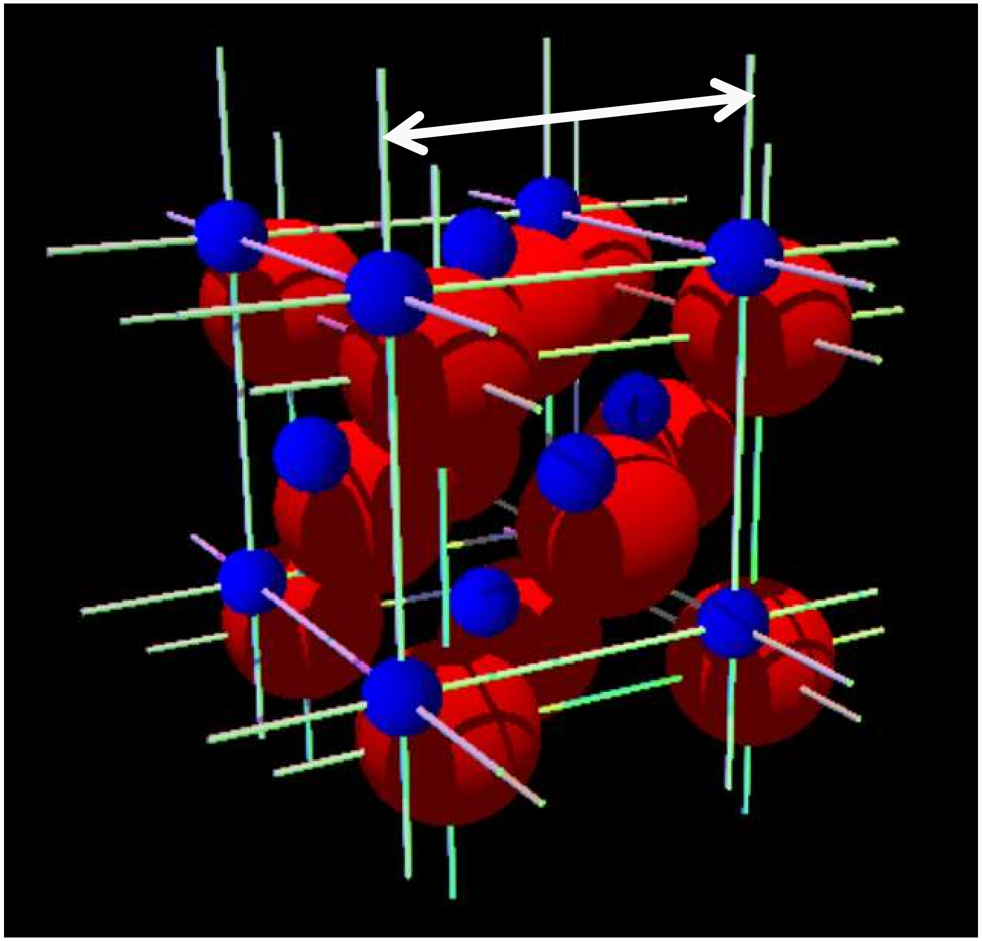
Semiconductors - chemical composition

- Covalent bonds: fill the last shell → 8 electrons
- Group IV semiconductors: Si, Ge (4+4 e^-)
- Binary semiconductors; two components
  - IV-IV: SiGe
  - III-V: GaAs, InP, GaN, InN (3+5 e^-)
  - II-VI: CdTe, ZnSe,... (2+6 e^-)
- Ternary semiconductors
  - III-V: $Al_{1-x}Ga_xAs$,
- Quaternary semiconductors
  - III-V: $In_{1-x}Ga_xAs_{1-y}P_y$, ...

IIb	IIIa	IVa	Va	VIa
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te

Section of periodic system of elements

Typical crystal structure III-V semiconductors

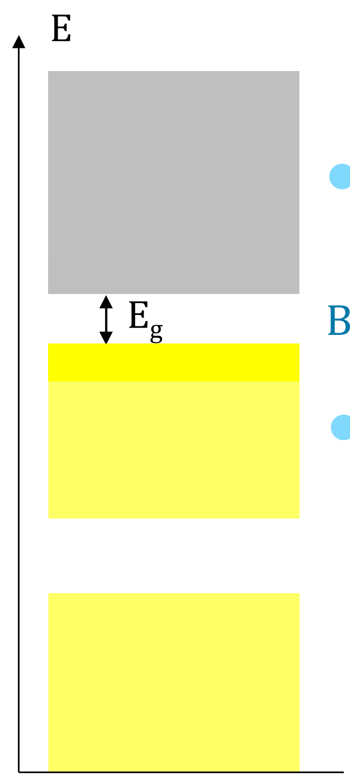


- The size of the unit cell of the crystal structure is characterized by a single number:
  the lattice constant

- Given the crystal structure and the lattice constant one can calculate the position of each atom.

Energy band structure semiconductor

- The band diagram of the crystal: an isolator.
- Energy bands formed by
  a large number of discrete bound states
  for electrons in the material. (Quasi-continuum)
- Conduction band: no electrons at Temperature = 0 K
- The Valence band: states completely filled
  at T = 0 K



- Conduction band

Bandgap

- Valence band

Energy band structure semiconductor

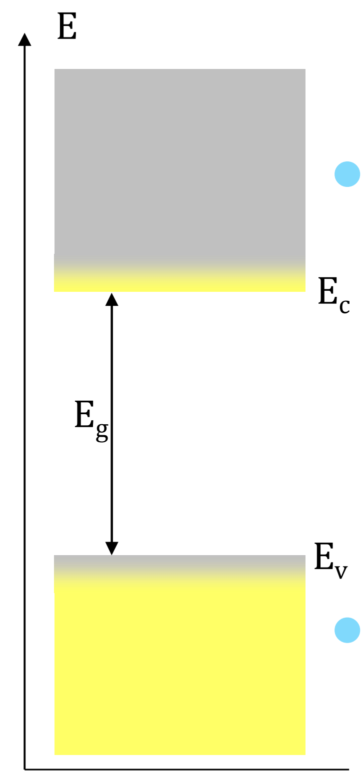
- In semiconductor: Bandgap E_g relatively small: thermal energy excites a few electrons from **Valence** band to the **Conduction** band

- At T > 0 Electrons in conduction band:

  some conductivity (highly temperature dependent)
  -> semiconductor

- Electrons promoted to the conduction band:
  open position in the Valence band
  Provides conductivity:
  - Hole

  = Quasi-particle positively charged



- Conduction band (CB)

Bandgap

$E_g = E_c - E_v$

- Valence band (VB)

Only consider the top of VB and bottom of CB

Carrier concentrations in intrinsic semiconductors

- Electrons and holes are named: **charge carriers;** or for short **carriers**

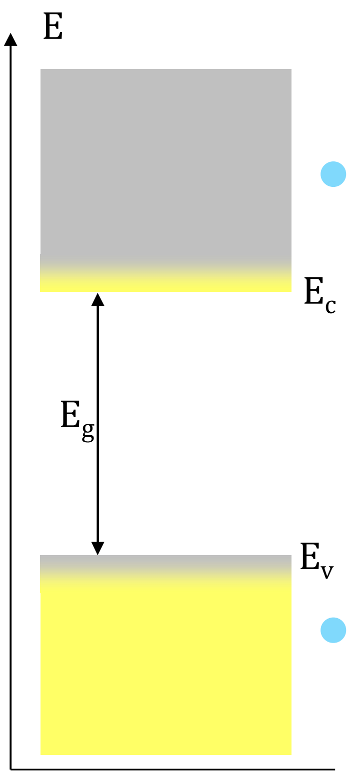
- Concentration electrons in conduction band: n_i
- Concentration holes in valence band: p_i

Intrinsic = pure material

- Electrons promoted to conduction band -> a hole in the valence band:

$$n_i = p_i \qquad n_i \cdot p_i = n_i^2$$

- The electrons and holes created by temperature will be neglected when <u>optical properties</u> of intrinsic materials are discussed



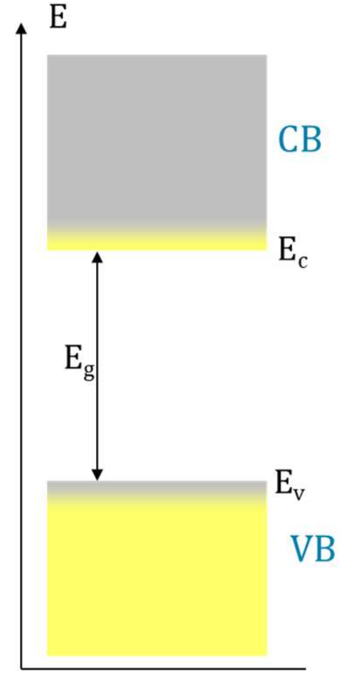
- Conduction band (CB)

Bandgap

- Valence band (VB)

Electrons: Effective mass, density of states conduction band

- Model: Electrons in CB and holes in VB **move** as free particles (compare with 3D cube quantum model)
- The difference with a free particle is the mass:
  - The electrons have an **effective mass** m_n^*
  - The **effective mass** depends on the material
    e.g. in GaAs: m_n^* = 0.067 x m_0 (m_0 is rest mass electron)



- Lowest energy levels/states for electrons in CB
  - **Density of states for electrons** $g_c(E)$ in CB (similar to 3D cube)

$$g_c(E) = \frac{4\pi (m_n^*)^{3/2}}{h^3} \sqrt{E - E_c} \quad E - E_c > 0$$

- # of states per unit volume in CB in a small energy interval at ΔE energy E : $g_c(E) \cdot \Delta E$
- # of states per unit volume in CB between energy E_1 and energyE_2: $\int_{E_1}^{E_2} g_c(E) \cdot dE$

Holes: Effective mass, density of states valence band

- The holes in the valence band each have an **effective mass** m_p^*
- Highest energy levels/states for holes in valence band
  - **Density of states for holes** in VB (similar to 3D cube)

$$g_v(E) = \frac{4\pi\left(m_p^*\right)^{3/2}}{h^3}\sqrt{E_v - E} \qquad E_v - E > 0$$

- # of states per unit volume in the VB in a small energy interval at ΔE energy E : $g_v(E) \cdot \Delta E$

- # of states per unit volume in the VB between energy E_1 and energy E_2: $\int_{E_1}^{E_2} g_v(E) \cdot dE$

Electrons and holes: energy, momentum and wavelength

- electrons in CB moving through crystal as free particles with effective mass m_n^* :

Momentum: $$|\vec{p}| = m_n^* \cdot |\vec{v}| = \hbar \cdot k = \frac{h}{\lambda}$$

All energy over E_c is kinetic energy

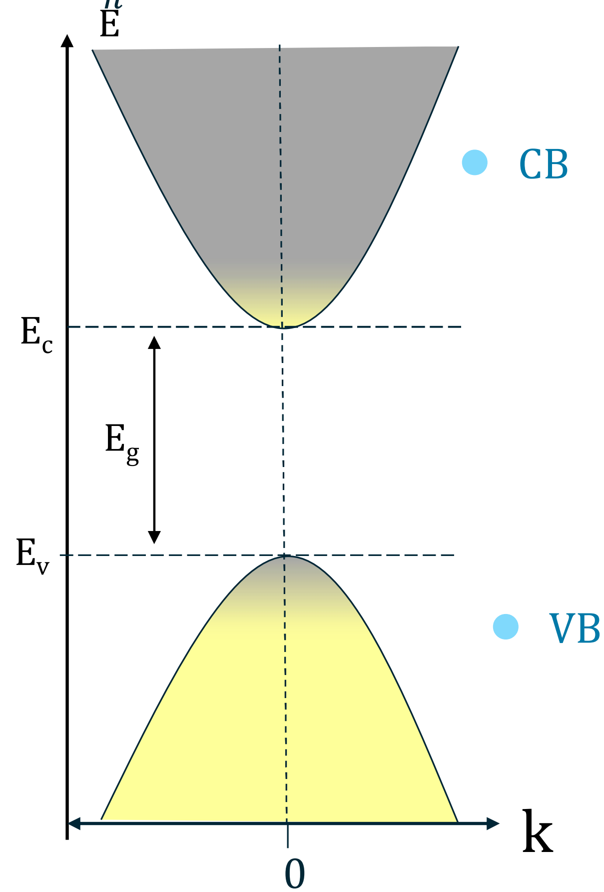
Energy: $$E - E_c = \frac{1}{2} m_n^* v^2 = \frac{p^2}{2 \cdot m_n^*} = \frac{\hbar^2 k^2}{2 \cdot m_n^*}$$

- holes in VB moving through crystal as free particles with effective mass m_p^* :

Momentum: $$|\vec{p}| = m_p^* \cdot |\vec{v}| = \hbar \cdot k = \frac{h}{\lambda}$$

All energy below E_c is kinetic energy

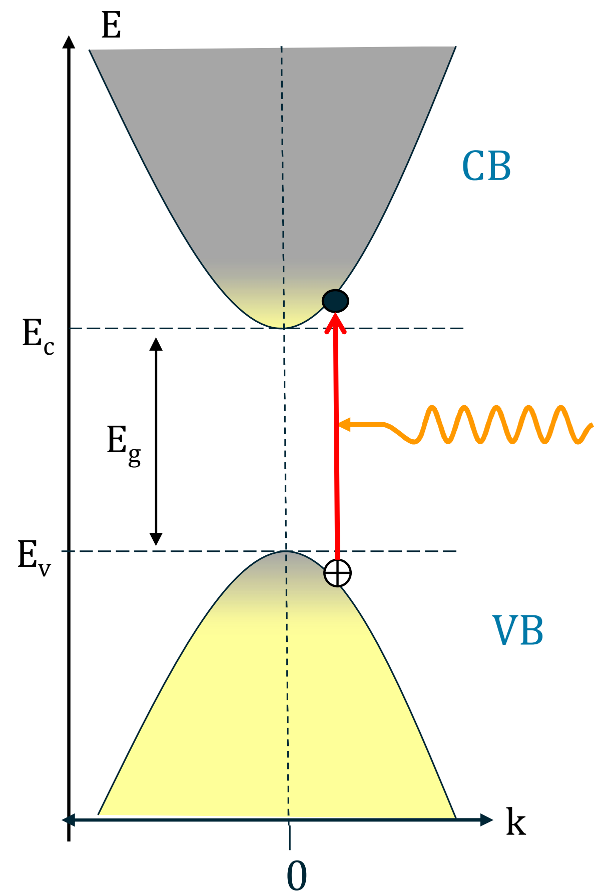
Energy: $$E_v - E = \frac{1}{2} m_p^* v^2 = \frac{p^2}{2 \cdot m_p^*} = \frac{\hbar^2 k^2}{2 \cdot m_p^*}$$



Light absorption in semiconductors

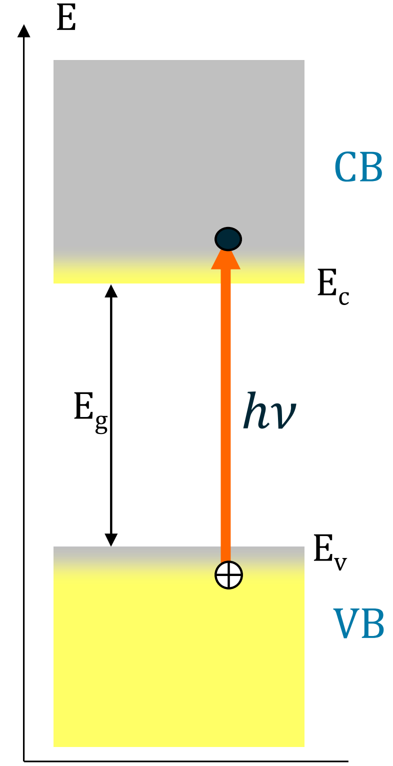
- Photon energy << Bandgap: little absorption
- Photon energy ~ Bandgap:
  large increase in absorption
  - Electrons from valence band are excited to conduction band

    k-vector of the electron **stays the same**.
    - Conservation of momentum
- **Direct bandgap**:
  Minimum CB at same k value as maximum VB in E-k diagram



Generation/recombination of excess carriers

- Carrier concentrations can be made much higher than thermal equilibrium values → **excess carriers**
- Excess electrons fill the states in the CB from the bottom of the CB
  Excess holes fill the states in the VB from the top of the VB
- Origin of excess carriers:
  - **Injection of carriers** (current, using diode structure)
  - **Absorbing photons** $h\nu \geq E_g$
- Excess carrier concentrations (electrically neutral) $\delta n = \delta p$
- No thermal equilibrium between CB and VB population however:
  - thermal equilibrium within CB and VB (quasi equilibrium)



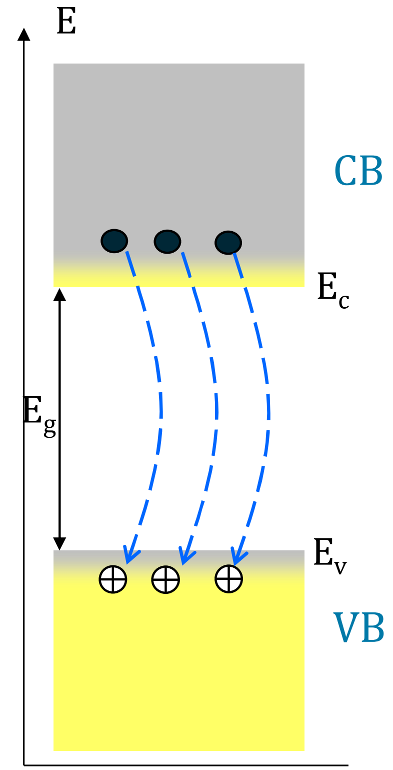
Excess electron-hole recombination

- Recombination:

The non-equilibrium situation will relax to equilibrium.

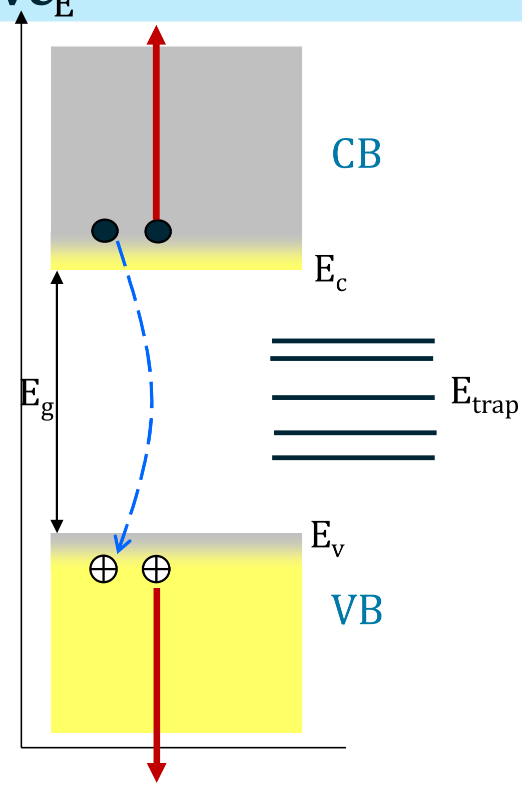
- Recombination rate
  for excess electrons and holes is the same

- -> lifetime of excess electrons and holes is the same



Excess electron-hole recombination processes – non radiative

- Recombination electron and hole
  - **Non-radiative processes**
  - At crystal defects (contaminations, lattice defects, surfaces)
    - These create states in the bandgap (trap states)
  - Three carrier collisions
    - Energy transferred to a different electron or hole: Auger recombination
  - A phonon (lattice vibration): via defects or surface states



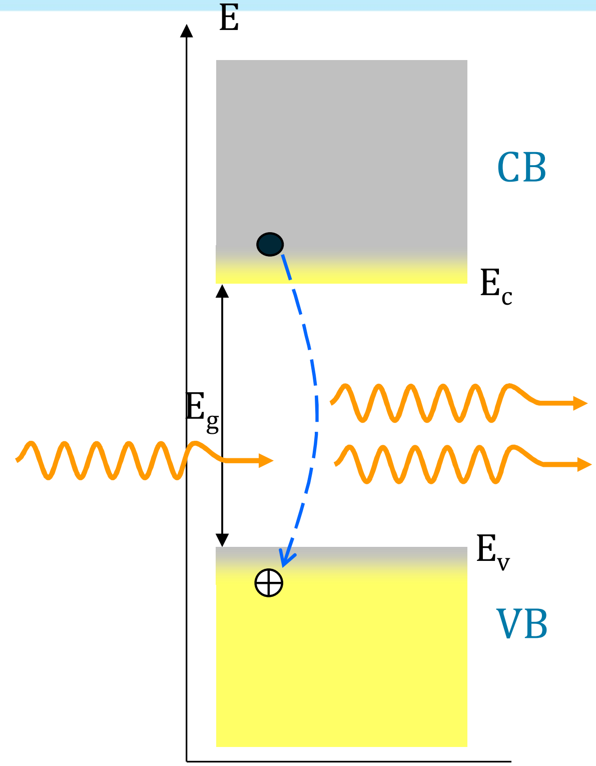
- **Total nonradiative recombination rate** U_{nr} # recombinations $m^{-3}s^{-1}$

Excess electron-hole recombination processes – radiative

- Energy released with spontaneous recombination event
  - As a photon: → radiative recombination U_r
- **Radiative processes**
- Spontaneous recombination and emission of photon
- Stimulated recombination and emission of a photon

k-vector of the electron and hole
must be the same – direct band gap

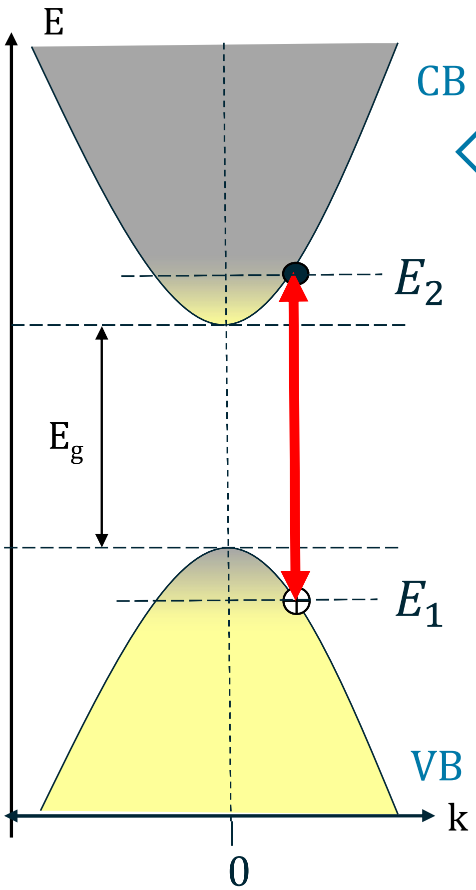
- Total recombination rate $U = U_r + U_{nr}$



- Lifetime of electron/hole: average time that a charge carrier stays in an excited state before recombining
  - Recombination process with shortest lifetime dominates

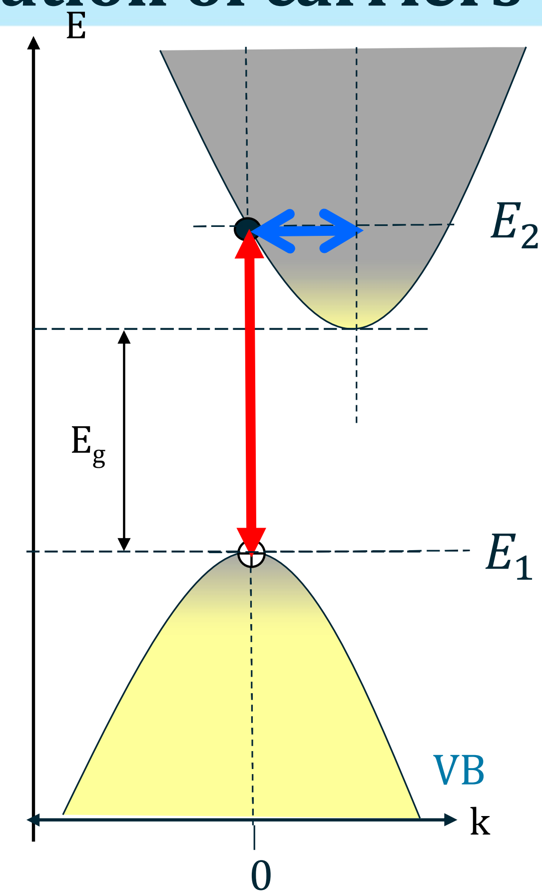
$$U \sim \frac{1}{\tau_{p,n}}$$

Direct and indirect bandgap – recombination of carriers



- Direct bandgap transition
  - Radiative recombination usually dominates
- Indirect bandgap transition
  - Radiative recombination improbable: photon can not take mismatch in k (momentum)
  - Difference in k-vector is compensated by phonon or third particle.

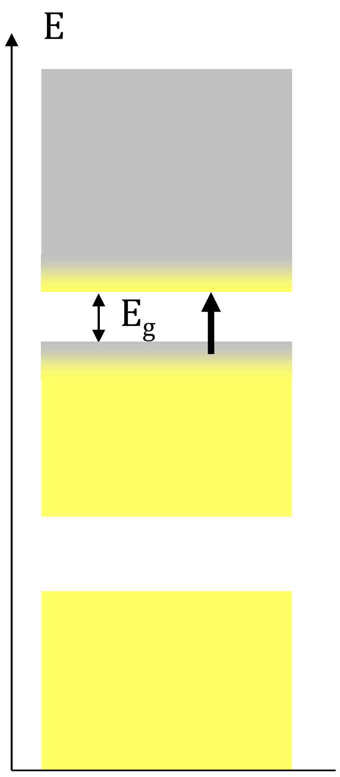
- Non-radiative processes dominate recombination in **indirect bandgap semiconductors**: e.g. Si



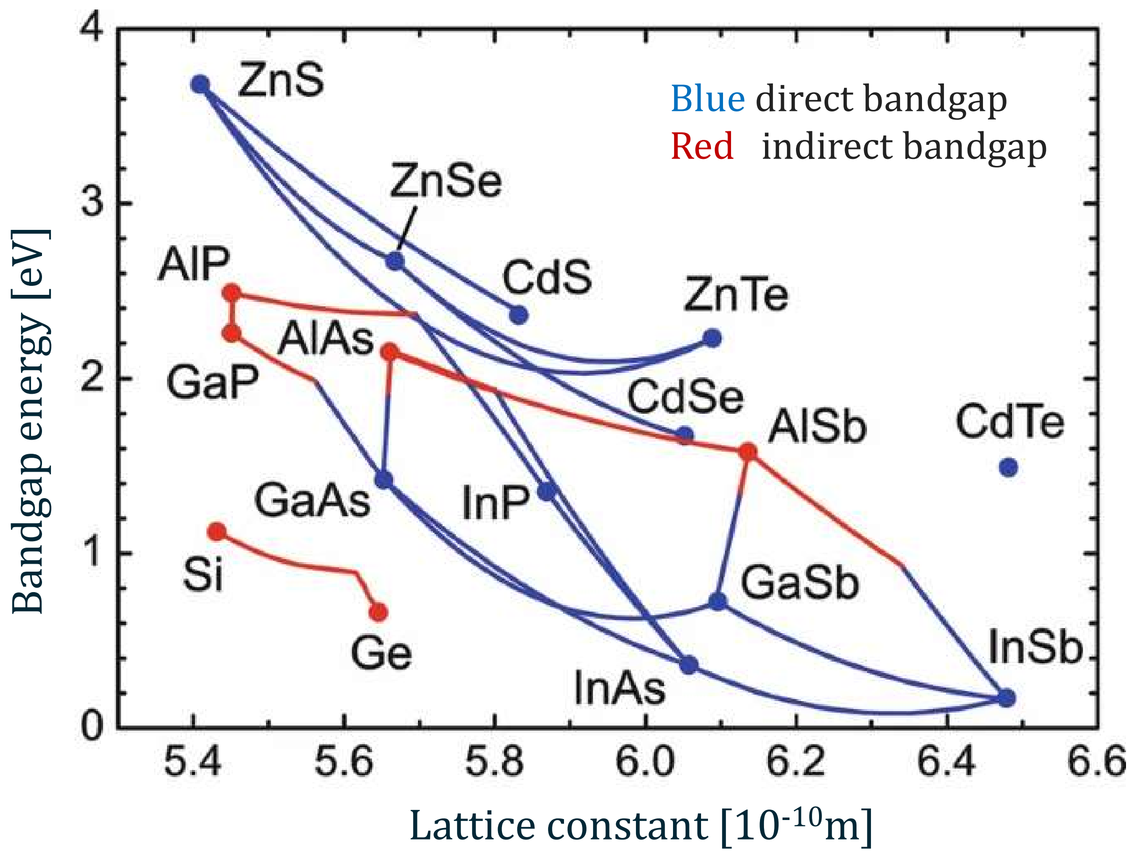
Types of semiconductor

- Classification according to
  - Chemical composition
    - single element, binary, ternary, … semiconductors
  - Band structure
    - Direct or indirect bandgap, size of bandgap
  - Doping
    - Intrinsic, p or n-type doping,

control of conductivity by electrons or holes

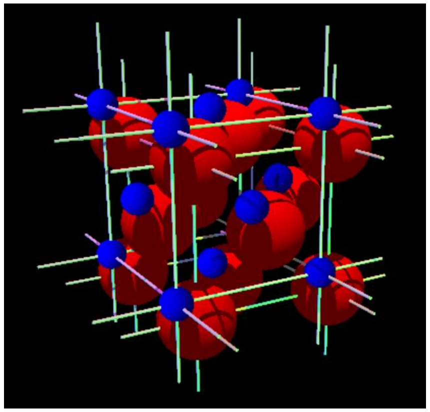


Bandgap – lattice constant – semiconductors



Böer, K.W., Pohl, U.W. (2023). Bands and Bandgaps in Solids. In: Semiconductor Physics. Springer, Cham. https://doi.org/10.1007/978-3-031-18286-0_8

Lattice constant:
size of cube shaped
unit cell in the crystal



Ternary material on lines between binary materials

Light absorption in semiconductors

- Direct band structure:
  sudden increase of absorption

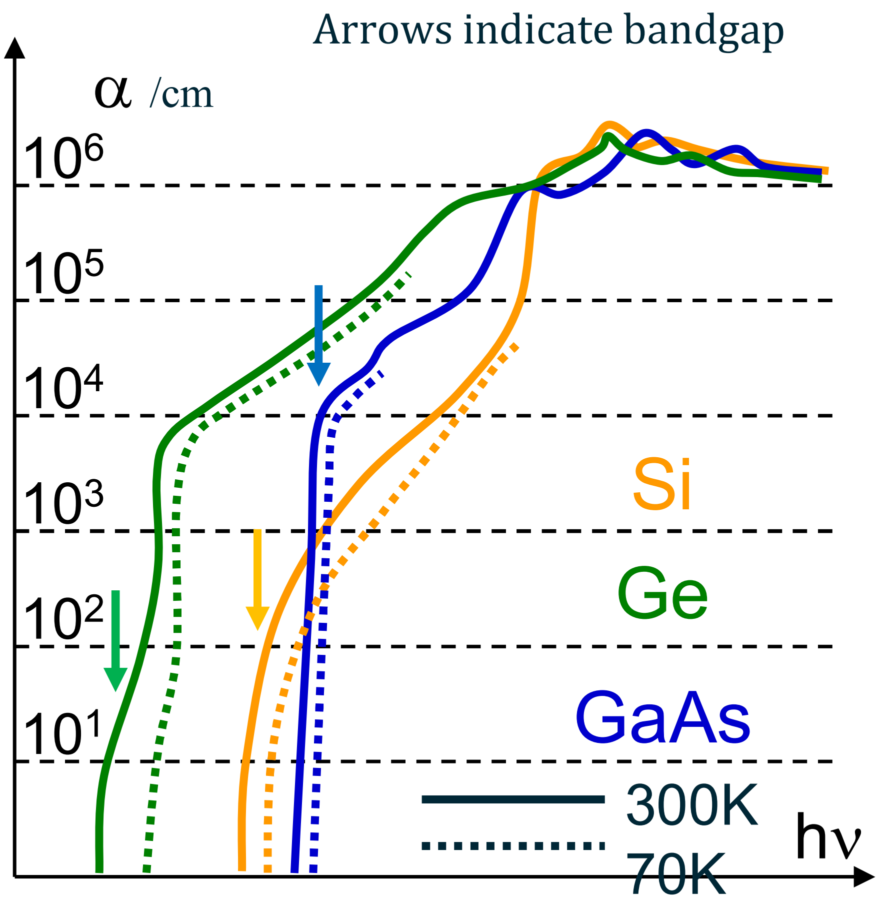
  GaAs 1.422 eV => 872 nm

- Indirect band structure:
  slow increase of absorption

  Si 1.11 eV => 1117 nm

  Ge 0.66 eV => 1879 nm

  Ge is close to direct bandgap



Intrinsic semiconductor – excess electrons in the CB

- We now know the where the energy levels are.
  Question: **which levels in the CB will excess electrons occupy**?
  - Thermal distribution within CB (quasi equilibrium)

Probability of finding an energy level occupied at energy E:

$$f_c(E) = \frac{1}{\exp\left(\frac{E - E_{Fn}}{k_B T}\right) + 1}$$

(Fermi-Dirac distribution, eq.10.19)

E_{Fn} is the **quasi-Fermi** energy for the CB

- Number of electrons in the CB per unit volume per unit energy:

$$N(E) = f_c(E) \cdot g_c(E)$$

- Total number of electrons in the CB per unit volume in thermal equilibrium :

$$\delta\mathrm{n} = \int_{E_c}^{\infty} f_c(E) \cdot g_c(E) \cdot dE$$

Neglect intrinsic carrier concentration

Intrinsic semiconductor – excess holes in the VB

- We now know the where the energy levels are.
  Question: which levels in the CB will excess electrons occupy?
  - Thermal distribution within CB (quasi equilibrium)

Probability of finding an energy level occupied at energy E:

$$f_v(E) = \frac{1}{\exp\left(\frac{E - E_{Fp}}{k_B T}\right) + 1}$$

(Fermi-Dirac distribution, eq.10.19)

E_{Fp} is the **quasi-Fermi** energy for the VB

- Number of holes in the VB per unit volume per unit energy:

$$\mathrm{P}(E) = \left(1 - f_v(E)\right) \cdot g_v(E)$$

- Total number of holes in the CB per unit volume in thermal equilibrium:

$$\delta p = \int_{-\infty}^{E_c} (1 - f_v) \cdot g_v(E) \cdot dE$$

Remember $\delta p = \delta n$

This links the two quasi-Fermi energy values E_{Fp} and E_{Fn}.

Example 14.1 - Excess electrons in GaAs

GaAs semiconductor material (intrinsic)

Bandgap: $E_g = 1.42\ eV = 2.275 \cdot 10^{-19} J$

Bottom CB: $E_c = 1.42\ eV$

Top VB: $E_v = 0.0\ eV$ $T = 300\ K$

effective mass $m_n^* = 0.067 \cdot m_0$

effective mass $m_p^* = 0.46 \cdot m_0$

$m_0 = 9.1 \cdot 10^{-31} kg$

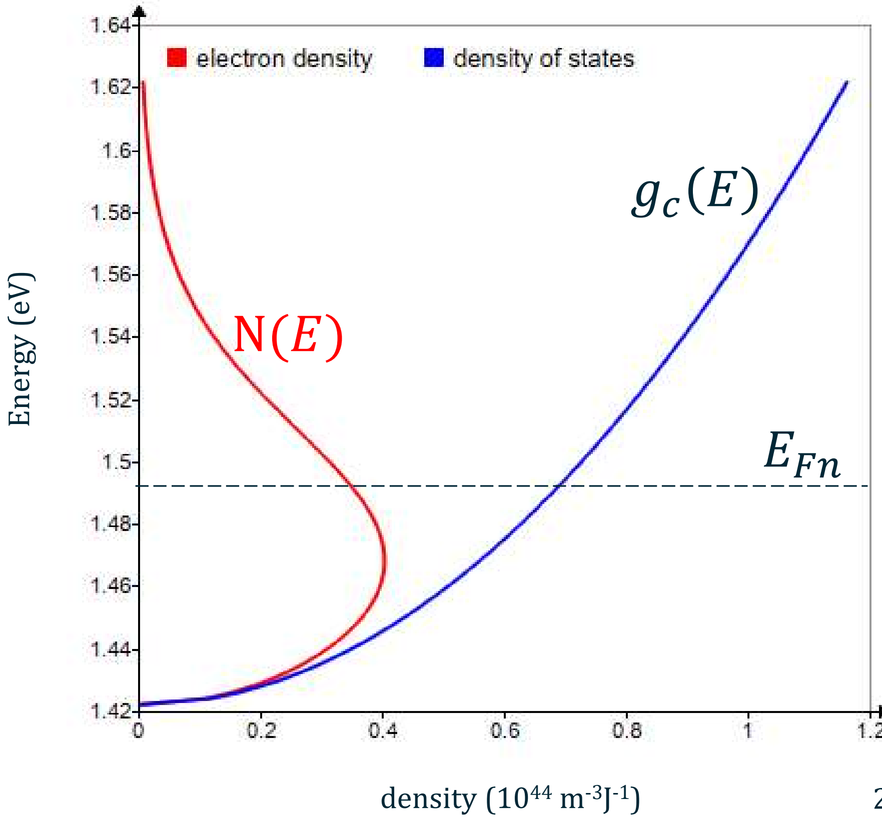
Assume e.g.

$E_{Fn} = 1.491\ eV$ $\delta n = \int_{E_c}^{\infty} f_c(E) \cdot g_c(E) \cdot dE$

numerical calculation: $\delta n = 6.16 \cdot 10^{23}\ m^{-3}$

concentration and quasi-Fermi level linked

Conduction band:



Example 14.1 GaAs excess holes

GaAs semiconductor material (intrinsic)

Bandgap: $E_g = 1.42\ eV = 2.275 \cdot 10^{-19} J$

Bottom CB: $E_c = 1.42\ eV$

Top VB: $E_v = 0.0\ eV$ $\quad T = 300\ K$

effective mass $m_n^* = 0.067 \cdot m_0$

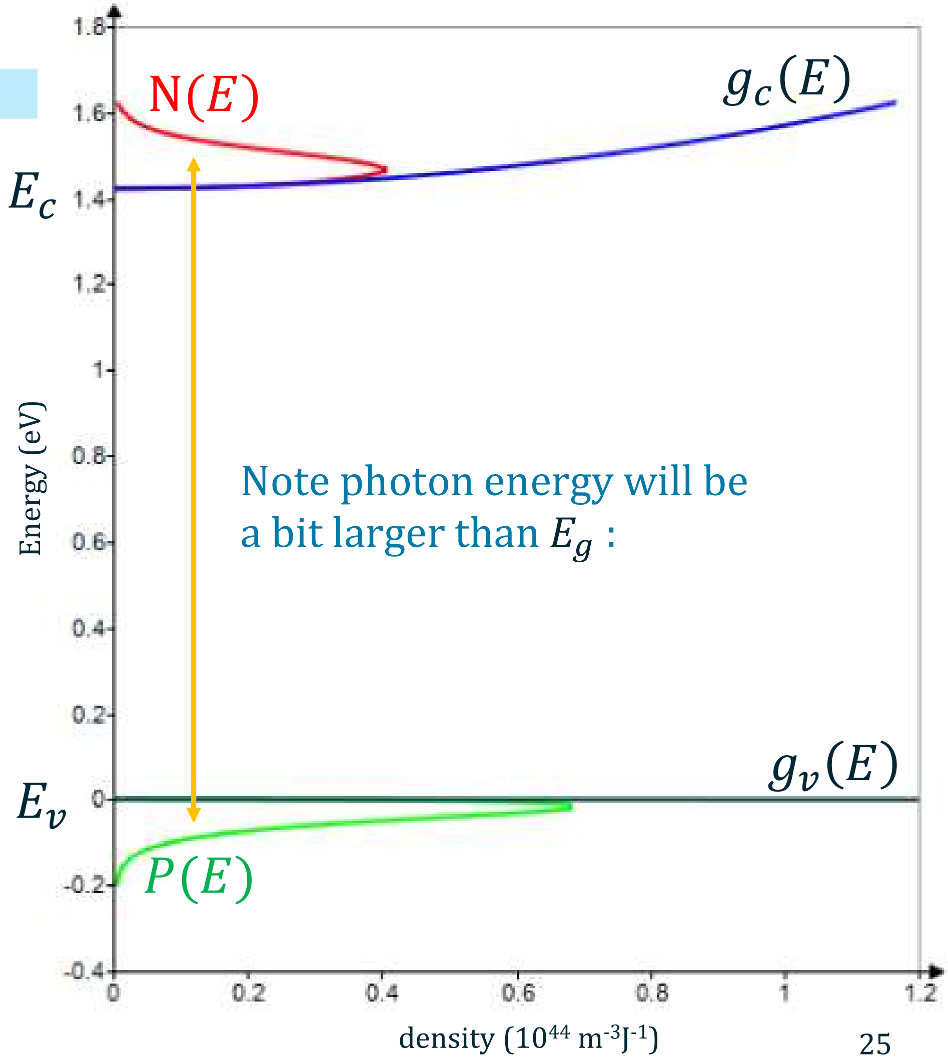
effective mass $m_p^* = 0.46 \cdot m_0$

$m_0 = 9.1 \cdot 10^{-31} kg$

$$\delta p = \delta n = \int_{-\infty}^{E_c} \left(1 - f_v(E)\right) \cdot g_v(E) \cdot dE$$

$$\delta p = \delta n = 6.16 \cdot 10^{23}\ m^{-3}$$

$E_{Fp} = 0.037 eV$ Just above E_v follows from:



Example 14.1 – GaAs thermal equilibrium

GaAs semiconductor material (intrinsic)

Bandgap: $E_g = 1.42\ eV = 2.275 \cdot 10^{-19} J$

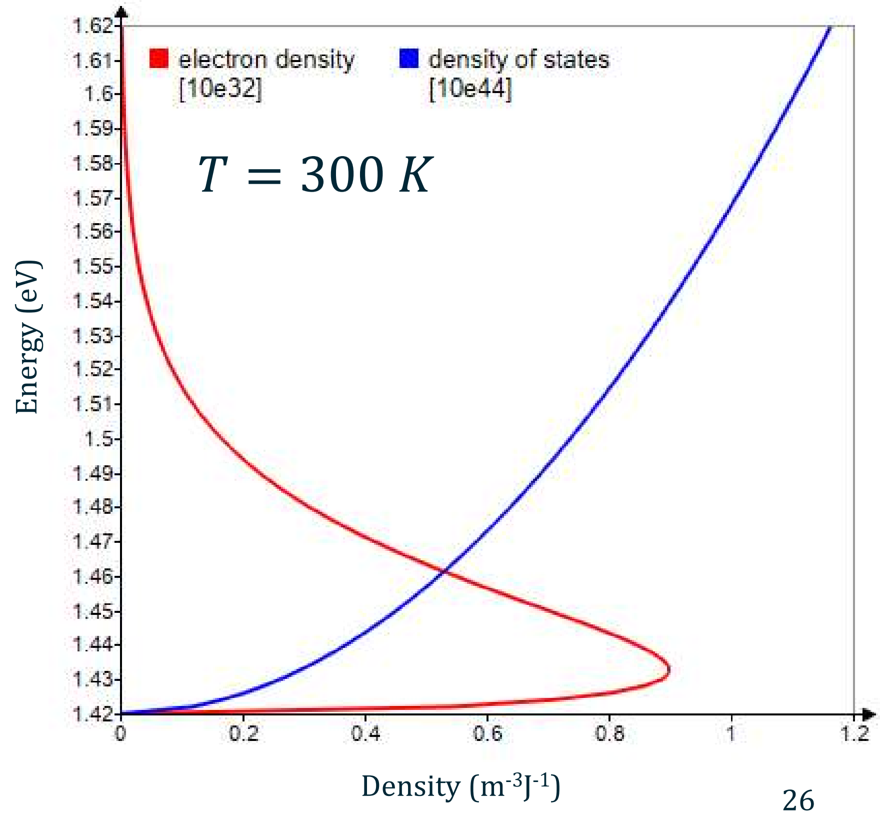
In thermal equilibrium (no excess carriers):

$$E_{fp} = E_{fn} \quad E_f = 0.74735\ eV$$

$$n_i = \int_{E_c}^{\infty} f_c(E) \cdot g_c(E) \cdot dE$$

$$n_i = p_i = 7.7 \cdot 10^{11}\ m^{-3}$$

This is a small number compared to the total number of (outer) electrons per unit volume in the material.



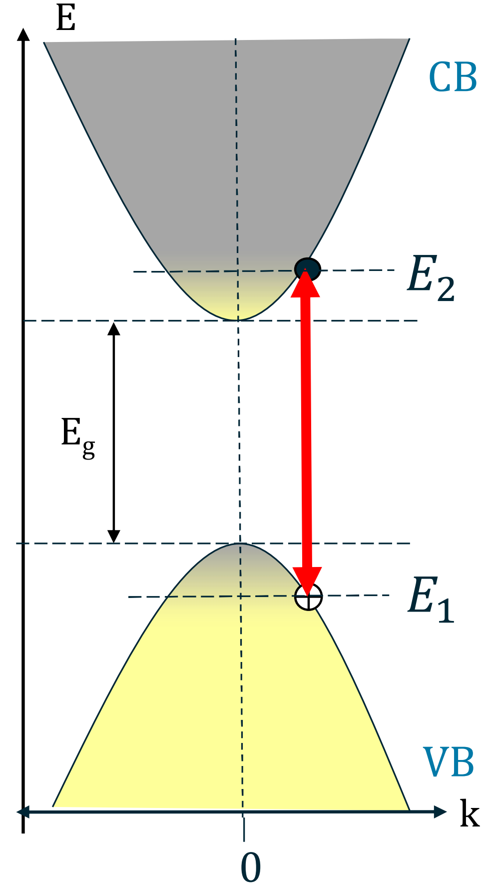
Condition for optical gain: Population-inversion

- To achieve population inversion in intrinsic material
  - Conduction band strongly filled = many free excess electrons
  - Valence band relatively empty = many free excess holes

- Pumping excess carriers in material:
  - Optically
  - Electrically: p-i-n double heterojunction:
    in forward bias current

- CB and VB out of thermal equilibrium
  - Quasi Fermi level E_{fn} for electrons in CB
  - Quasi Fermi level E_{fp} for holes in VB

- Question? – what is the concentration of excess carriers needed to achieve inversion / optical gain for a transition between levels at E_1 and E_2 with the same k



Probabilities finding excess electrons and holes

- Probability finding an electron at energy E_2 in conduction band:

$$f_c(E_2) = \frac{1}{\exp\left(\frac{E_2 - E_{Fn}}{k_B T}\right) + 1}$$

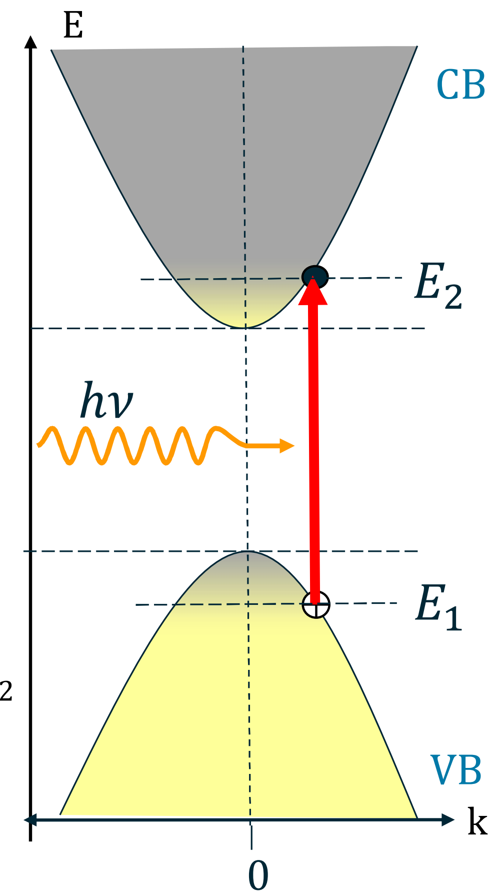
- Probability of finding a hole at energy E_1 in valence band:
  = probability of not finding an electron at E_1 :

$$1 - f_v(E_1) = 1 - \frac{1}{\exp\left(\frac{E_1 - E_{Fp}}{k_B T}\right) + 1}$$

Optical gain in a semiconductor- Absorption rate

Absorption rate:

$$R_{ab} = B_{12} \cdot f_v(E_1)\, g_v(E_1) \cdot \left(1 - f_c(E_2)\right) g_c(E_2) \cdot \rho_p(E_2 - E_1)$$



B_{12} Einstein coefficient - transition probability for absorption

$f_c(E_2)$ Fermi distribution quasi Fermi level E_{Fn}

$f_v(E_1)$ Fermi distribution quasi Fermi level E_{Fp}

$g_v(E_1)$ $g_c(E_2)$ Density of states valence band at E_1, conduction band at E_2

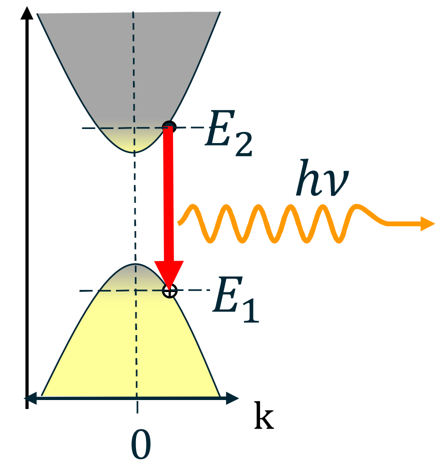
$\rho_p(E_2 - E_1)$ Density of photons with correct energy E_2 - E_1

Spontaneous and stimulated emission rates

Spontaneous emission rate

$$R_{sp} = A_{21} \cdot f_c(E_2)\, g_c(E_2) \cdot \big(1 - f_v(E_1)\big)\, g_v(E_1)$$

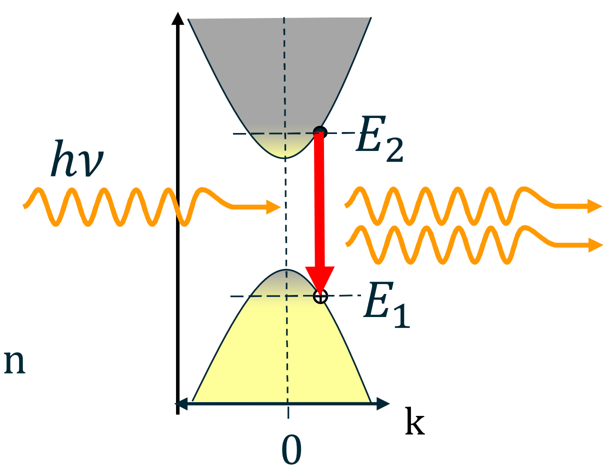
A_{21} Einstein coefficient - transition probability for spontaneous emission



Stimulated emission rate

$$R_{st} = B_{21} \cdot f_c(E_2)\, g_c(E_2) \cdot \big(1 - f_v(E_1)\big)\, g_v(E_1) \cdot \rho_p(E_2 - E_1)$$

B_{21} Einstein coefficient - transition probability for stimulated emission



Condition for optical gain

Rate for stimulated emission > Rate for absorption $R_{st} > R_{ab}$

$$B_{21} \cdot f_c(E_2)\, g_c(E_2) \cdot \big(1 - f_v(E_1)\big)\, g_v(E_1) \cdot \rho_p(E_2 - E_1) \;>$$
$$B_{12} \cdot f_v(E_1)\, g_v(E_1) \cdot \big(1 - f_c(E_2)\big)\, g_c(E_2) \cdot \rho_p(E_2 - E_1)$$

$$\Downarrow$$

$$f_c(E_2) \cdot \big(1 - f_v(E_1)\big) > f_v(E_1) \cdot \big(1 - f_c(E_2)\big)$$

Substituting the Fermi functions leads to the condition: $\boxed{E_{Fn} - E_{Fp} > (E_2 - E_1) \geq E_g}$

Net optical gain when: quasi-Fermi levels are separated by more than the band gap:
inversion condition for semiconductors

- Transparency if $E_{Fn} - E_{Fp} = E_g$ Gain if $E_{Fn} - E_{Fp} > E_g$
  - Excess electron and hole concentration: $\delta n = \delta p = n = p \sim 2 \cdot 10^{18}\ \mathrm{cm}^{-3}$
- Photon energy from E_G to a bit above

Optical gain calculation - principle

Net rate of amplification is: $R_{net} = R_{st} - R_{ab}$

$$R_{net} = B_{21} \cdot \underline{g_c(E_2) g_v(E_1)} \cdot \left(f_c(E_2) - f_v(E_1)\right) \cdot \underline{\rho_p(E_2 - E_1)}$$

The density of states for the carriers.
Determined by **material and its structure**

The density of photons.
In a laser:
Determined by the laser cavity

Structuring at the level of the electron wavelength influences the density of states

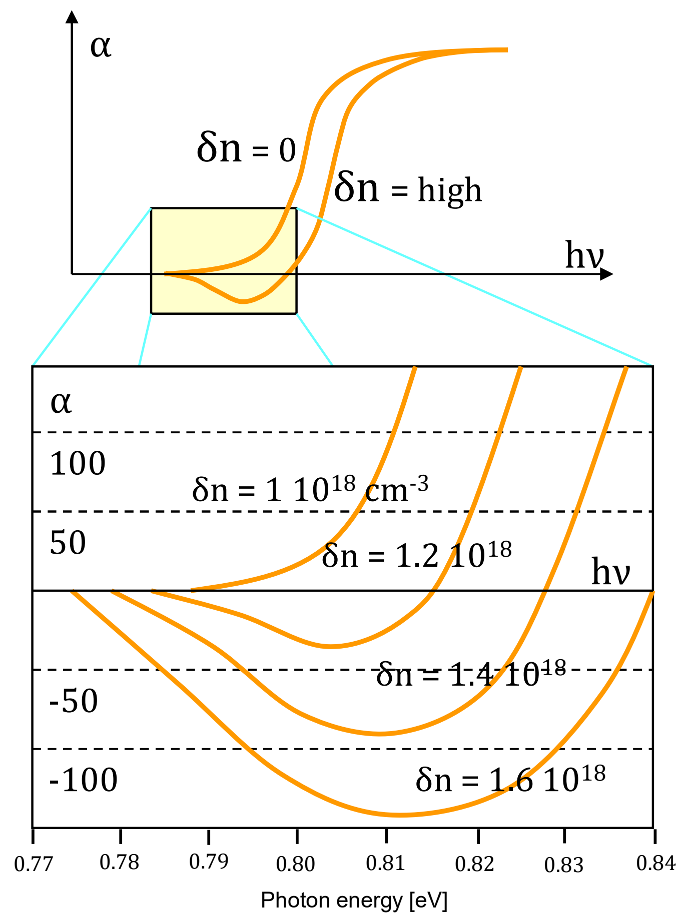
Structuring at the level of a fraction of the scale of the wavelength of light

The optical gain: $$g_{mat} = \frac{B_{21}}{v_g} g_c(E_2) g_v(E_1) \cdot \left(f_c(E_2) - f_v(E_1)\right)$$

v_g is the group velocity of the light

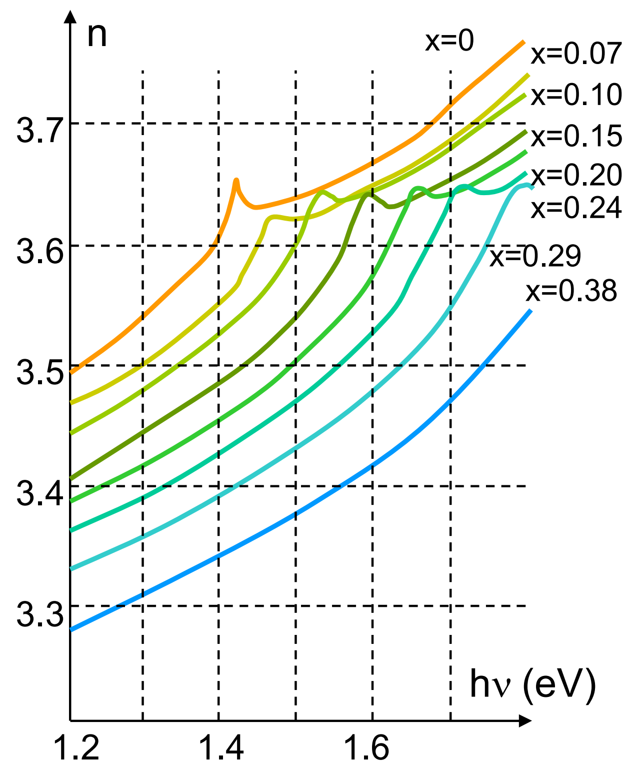
Stimulated emission in semiconductors

- Population inversion
  - Many excess holes in valence band
  - Many excess electrons in conduction band
  - No thermal equilibrium $\delta n = \delta p$
- Stimulated emission > absorption
  - Occurs when $\hbar\omega > E_G$
- Gain (for real amplifier InGaAsP structure)
  - Order of magnitude: 100 cm^{-1}
  - Much smaller than α for large photon energy



Refractive index of semiconductors

- High refractive index
  - n = 3.0 - 4.0
  - Large bandgap => low n
  - n = wavelength dependent (dispersion)
  - Increases with photon energy
- Refractive index peak at bandgap
  - Change in absorption also changes the refractive index (K-K)
- Example. $Al_xGa_{1-x}As$
  - n decreases for increasing x



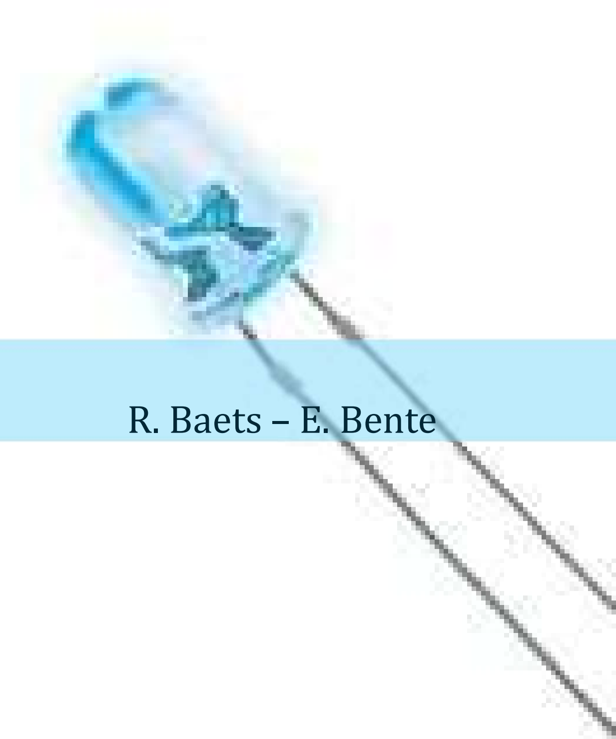
Influences on optical properties of semiconductors

- Refractive index n can be influenced by
  - Temperature (thermo-optic effect)
  - Electron and hole concentration (the gain and absorption curve, plasma effect,…)
  - Static electric field (Pockels effect, Kerr effect, Stark effect)
  - mechanical deformation → stress

- The bandgap also depends on these parameters: influence on absorption and hence refractive index

- Anisotropy of crystal structure
  - Properties depend on polarization and direction of light

Photonics



R. Baets – E. Bente

Semiconductor light sources – Part B

PN-junctions
Light emission from pn-junctions

Content

- How to achieve high excess carrier concentrations?
  - pn-junction and heterojunctions
    (also useful for detectors)

- Semiconductor material systems

Doped semiconductors – n doping – in equilibrium

- Add low concentration of atoms with a weakly bound outer electron.

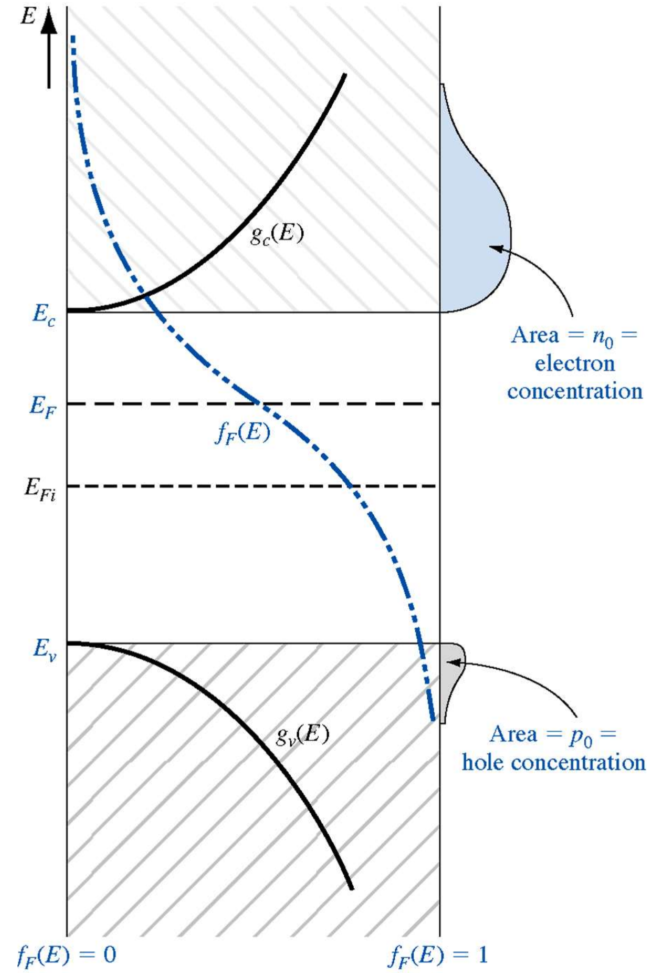
- Thermal equilibrium
  - electron concentration in CB up
  - Hole concentration in VB down

- Fermi-level goes up!

- Doping concentration higher than intrinsic material
  – conductivity up

$$n_0 > p_0 \qquad n_0 \cdot p_0 = n_i^2$$

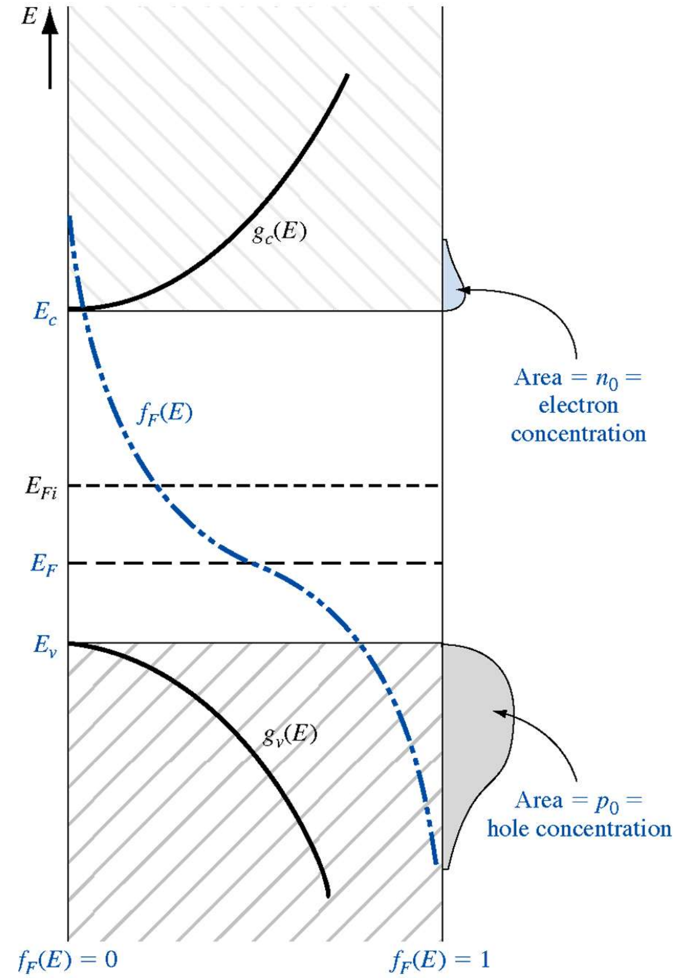
n_i is the carrier concentration in intrinsic (undoped material)



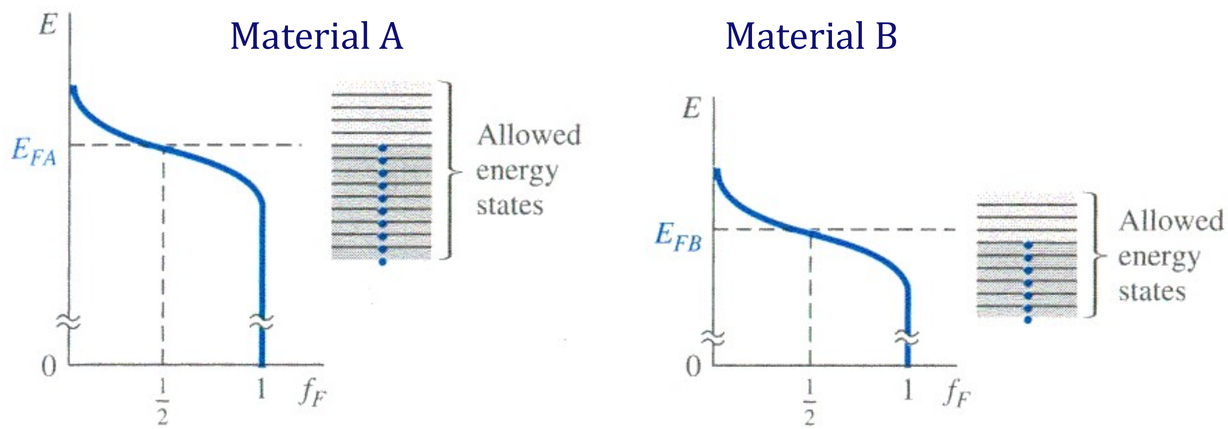
Doped semiconductors – p doping – in equilibrium

- Add low concentration of atoms that can bind a free electron.
- Thermal equilibrium
  - electron concentration in CB down
  - Hole concentration in VB up
- Fermi-level goes down!
- Doping concentration higher than intrinsic material – conductivity up

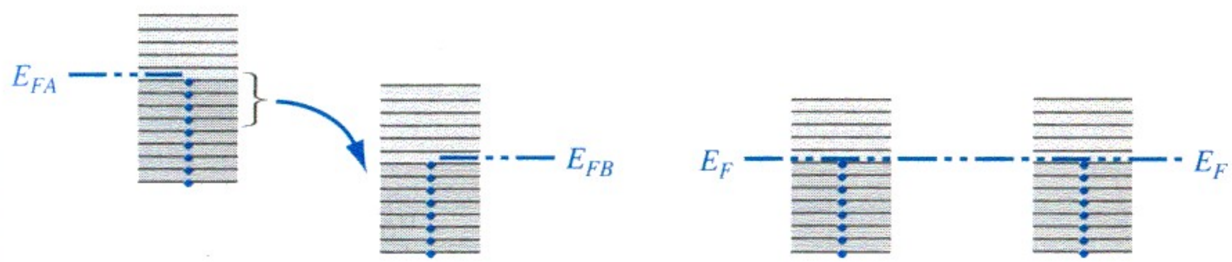
$$n_0 < p_0 \qquad n_0 \cdot p_0 = n_i^2$$



Relevance of the Fermi-energy level



- One Fermi-level in a single quantum system



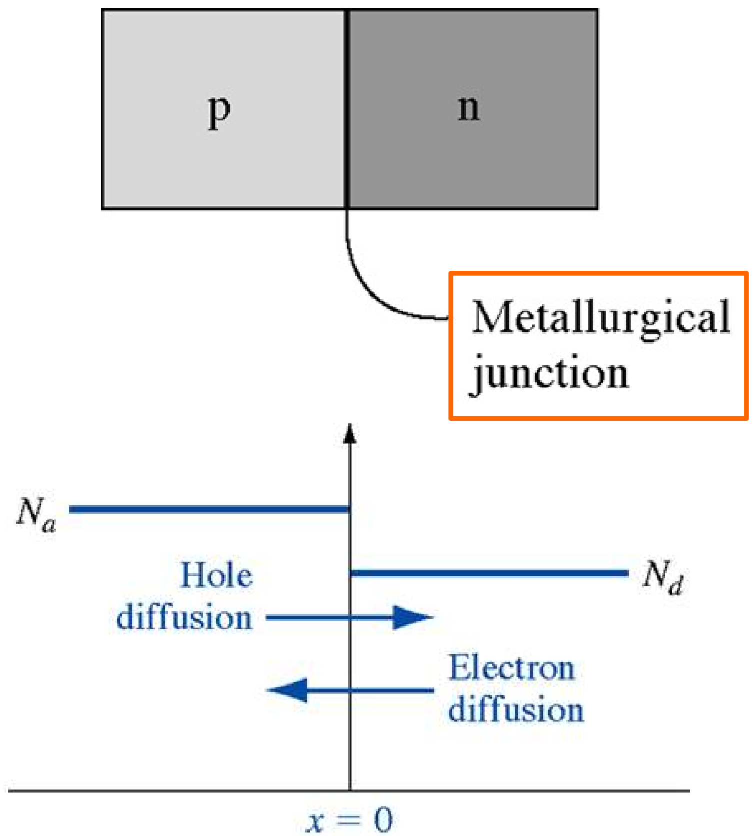
In thermal equilibrium the Fermi-energy is a constant in the system!

The pn–junction

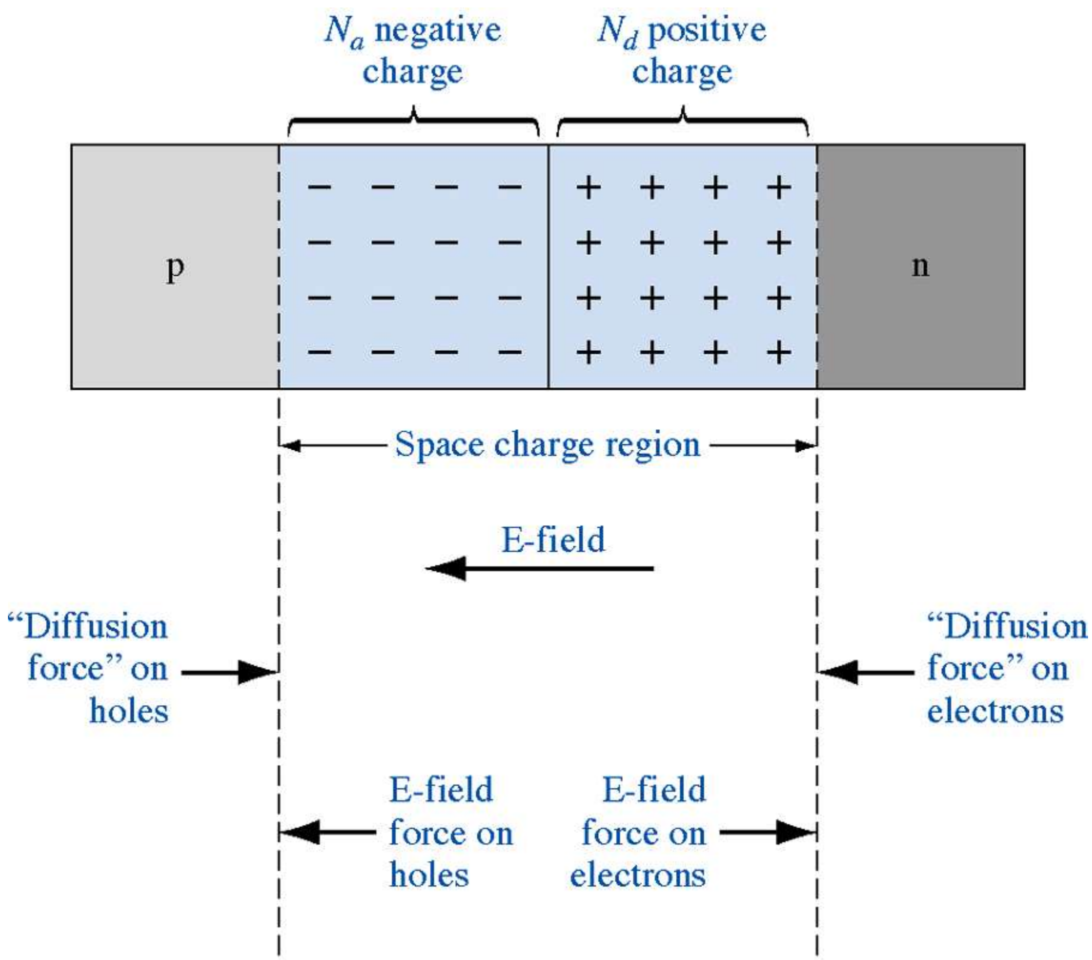
- p-type semiconductor:
  high concentration of holes p
- n-type semiconductor:
  high concentration of electrons n
- typical doping density :
  $10^{17}/\mathrm{cm}^3$ - $10^{19}/\mathrm{cm}^3$

N_a acceptor doping concentration

N_d donor doping concentration

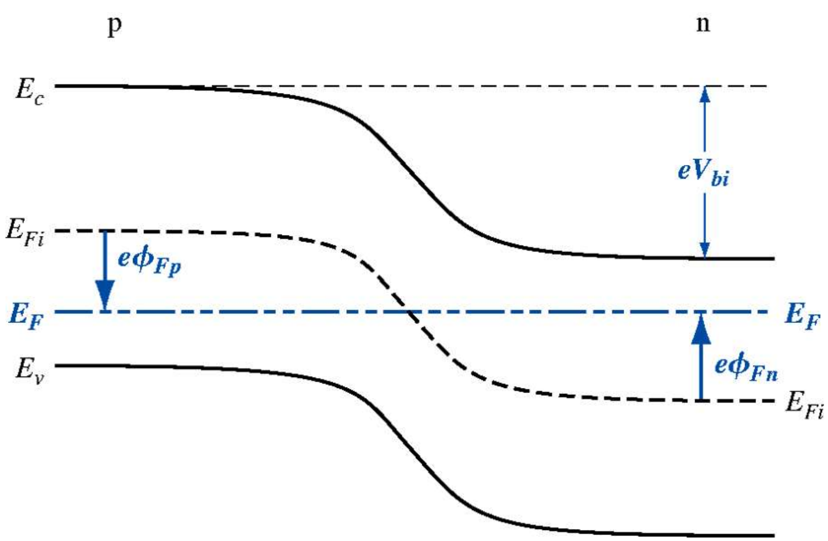


Balance between diffusion forces and electric field



Built-in potential barrier of the pn-junction

- No applied voltage – thermal equilibrium => Fermi-level is constant



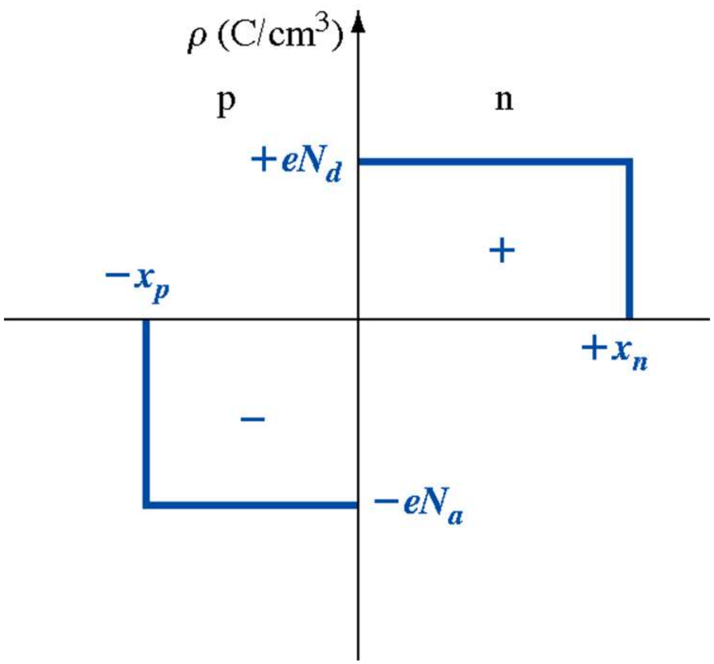
$$V_{bi} = |\phi_{Fn}| + |\phi_{Fn}|$$

$$V_{bi} = \frac{kT}{e} ln\left(\frac{N_a N_d}{n_i^2}\right)$$

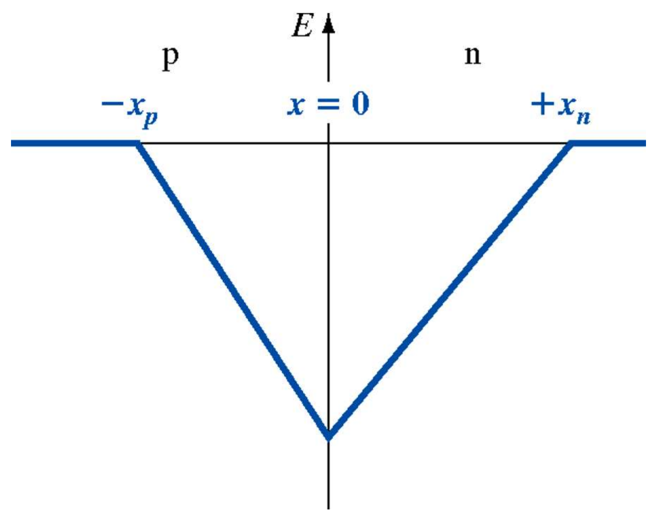
n_i is the carrier concentration in intrinsic (undoped material)
N_a is the p doping concentration
N_d is the n-doping concentration

Charge distribution and electric field in the depletion region

- Relation between potential $\phi(x)$, charge density $\rho(x)$ and electric field $E(x)$:

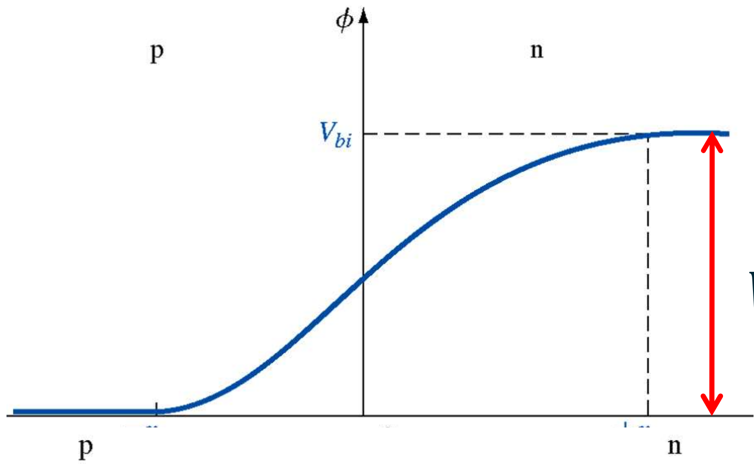


$$\frac{d^2\phi(x)}{dx^2} = -\frac{\rho(x)}{\epsilon_S} = -\frac{dE(x)}{dx}$$



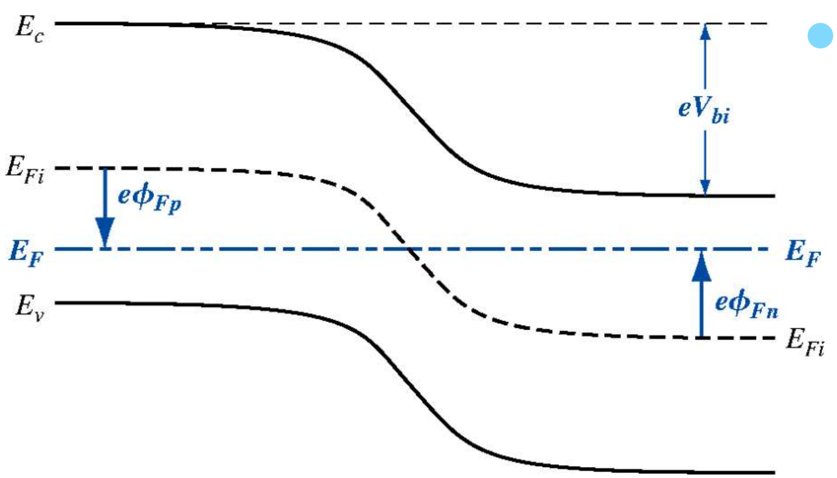
- The amount of charge at both sides of the junction is equal: $N_d x_n = N_a x_p$

Potential in the pn-junction



- The electrical potential φ across the junction (proportional to energy of positive unit charge)

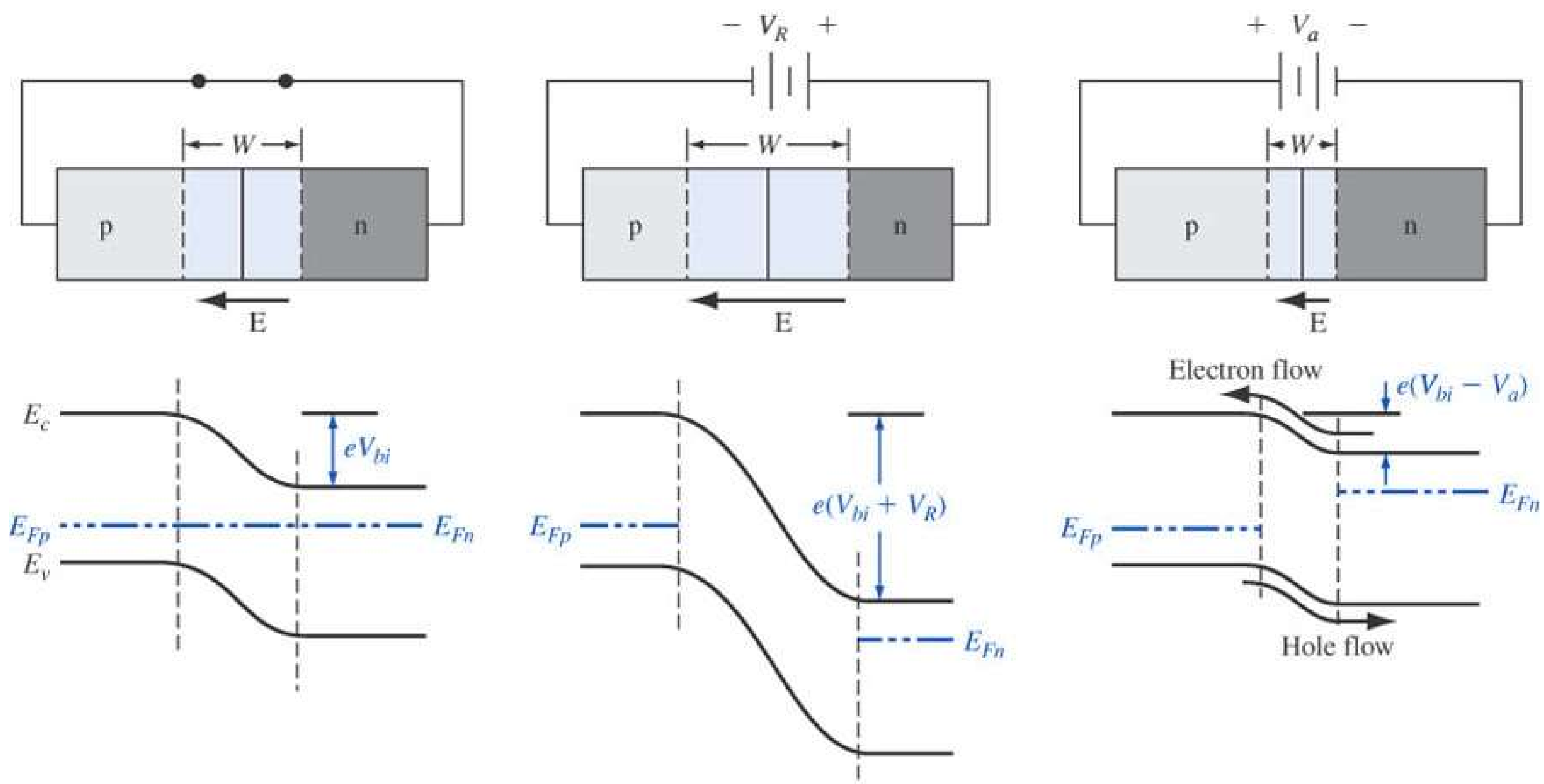
$$V_{bi} = |\phi(x = x_n)| = \frac{2}{2\varepsilon_S}\left(N_d x_n^2 + N_a\, x_p^2\right)$$



- The energy of electrons across the junction (energy of negative unit charge) in the CB and VB

- band bending

pn-junction – Reverse and Forward bias



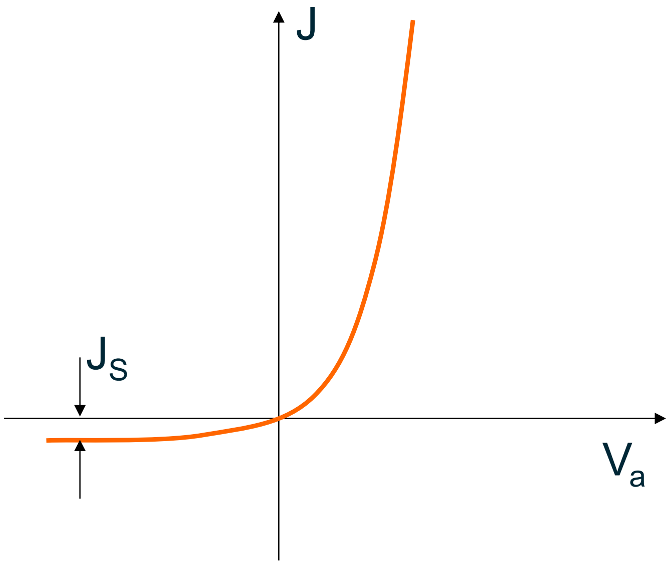
- unbiased
- Reverse biased
- Forward biased

I–V characteristic of a pn–junction

- Shockley-equation

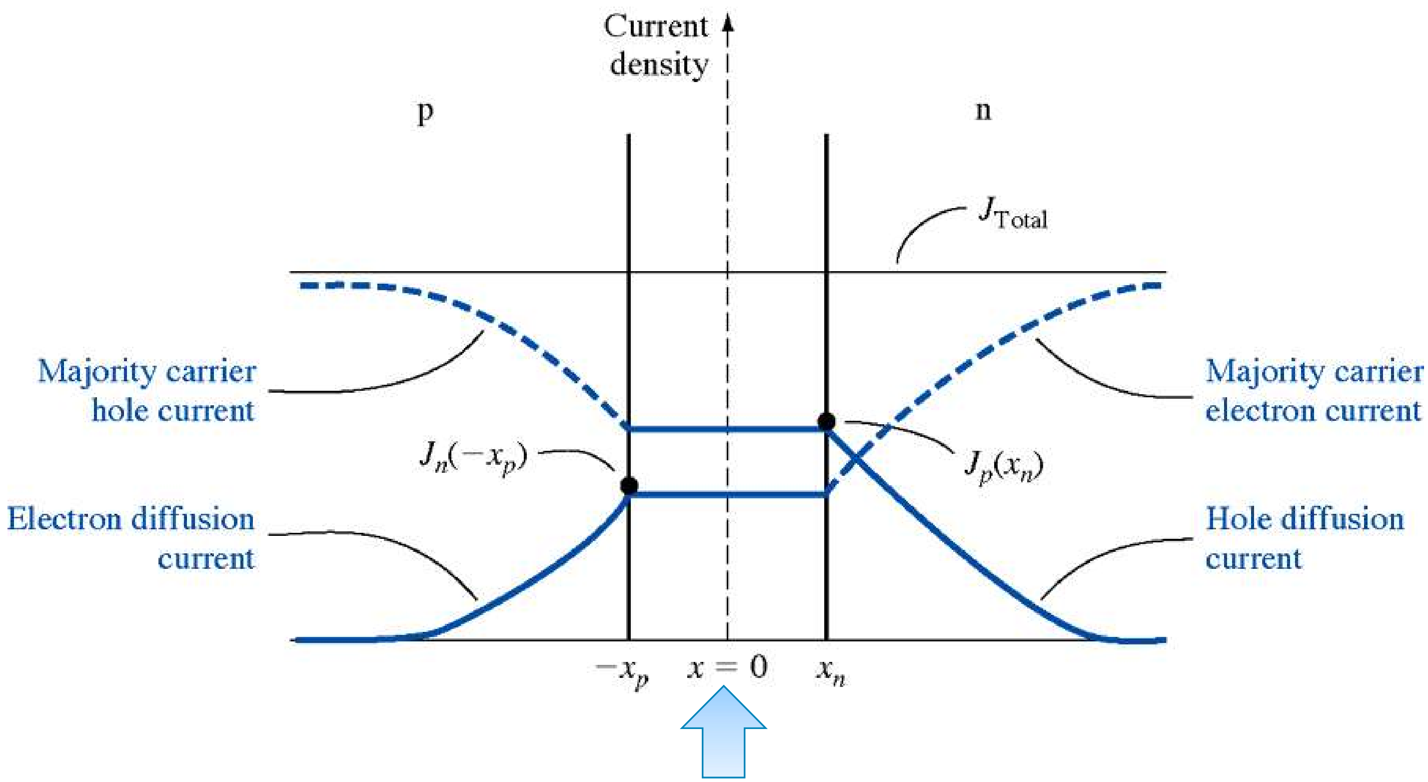
$$J = J_S\left[exp\left(\frac{eV_a}{k_BT}\right) - 1\right]$$

$$J_S = e\left(\frac{D_n n_{p0}}{L_n} + \frac{D_p p_{n0}}{L_p}\right)$$



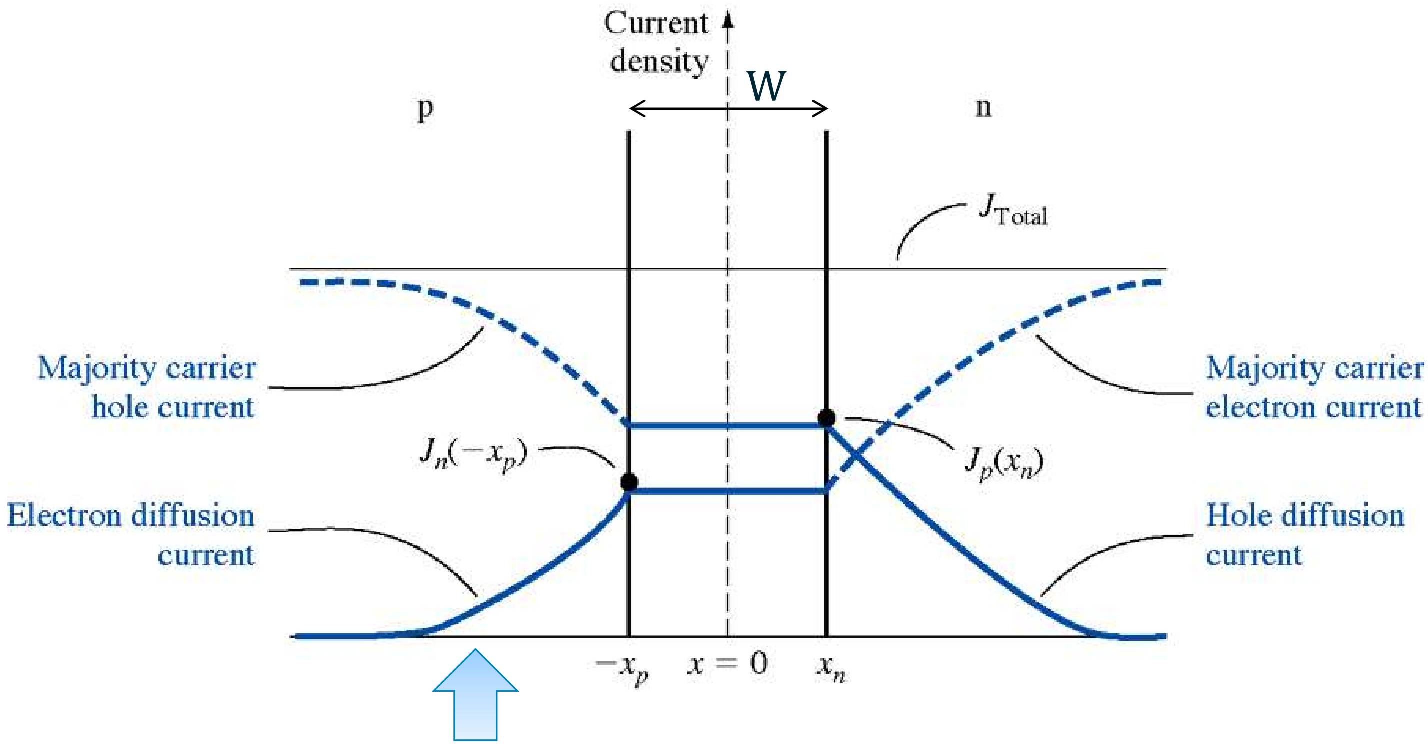
  - J_S is the ideal saturation current density
  - D_n, D_p electron, hole diffusion coefficient
  - L_n, L_p electron, hole diffusion length
  - n_{p0} thermal equilibrium electron concentration in p doped region
  - p_{n0} thermal equilibrium hole concentration in n doped region

Current density in pn-junction under forward bias



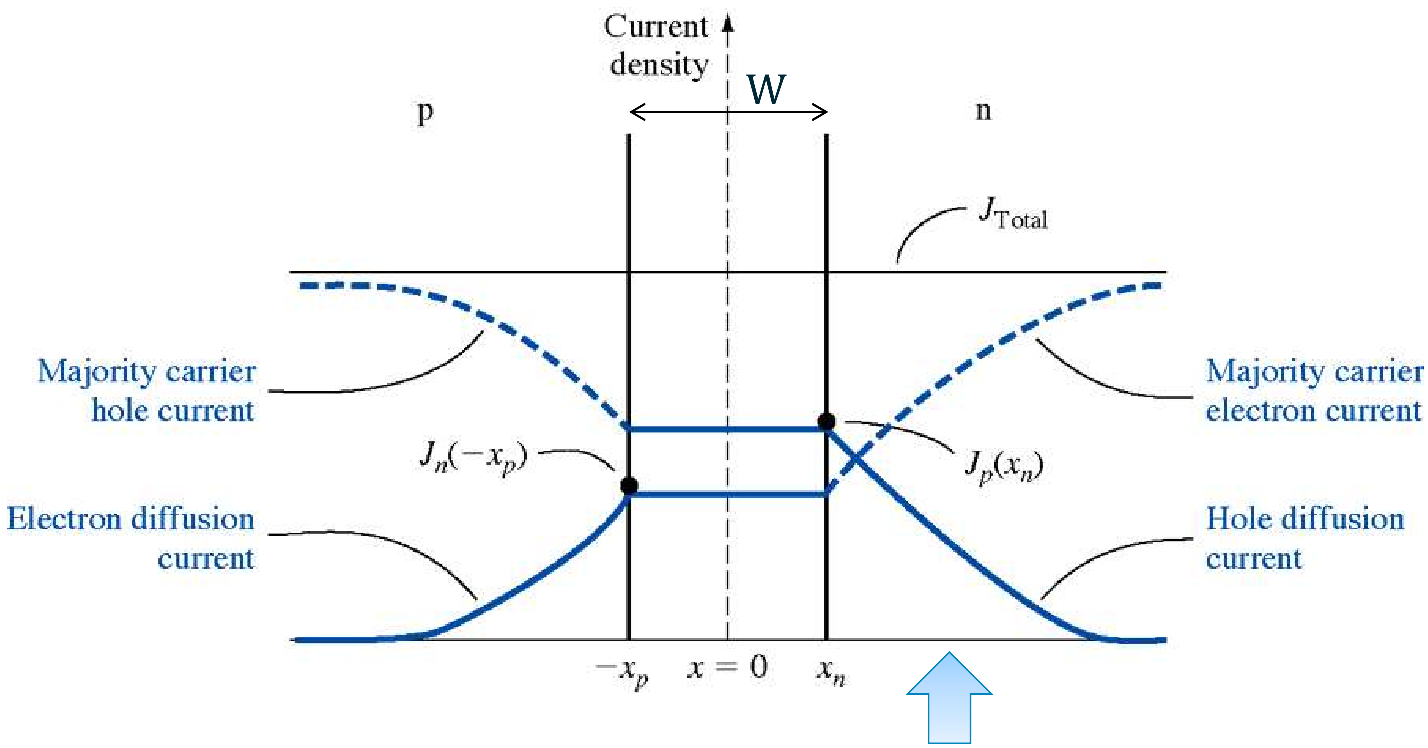
- Depletion layer ($-x_p$ to x_n):
  carriers move fast due to strong electric field
  constant current density + high speed -> low carrier density

Current density in pn-junction under forward bias



- p-region ($x < -x_p$): injected excess electrons recombine with majority holes over region of length $\sim L_n \gg W$

Current density in pn-junction under forward bias



- n-region ($x < -x_p$): injected excess holes recombine with majority electrons over region of length $\sim L_p \gg W$

Light emission and gain in pn-junction?

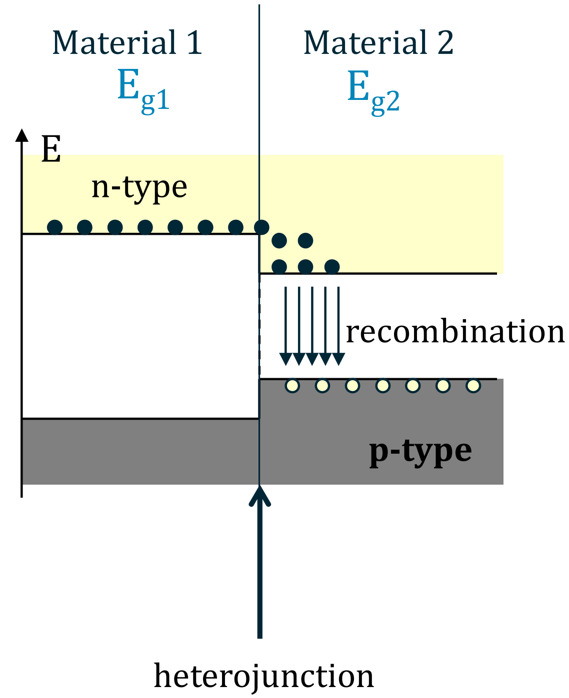
- Excess electron-hole recombination mainly in p or n region
  - Doping (p and n) increases absorption significantly!
  - The free carriers can absorb light
  - ideally: Recombination in undoped (intrinsic) material

- Recombination spreads out over diffusion length
  - difficult to achieve sufficient concentration of excess carriers to achieve transparency and gain

- Solution: use the double heterostructure

Heterojunction – single

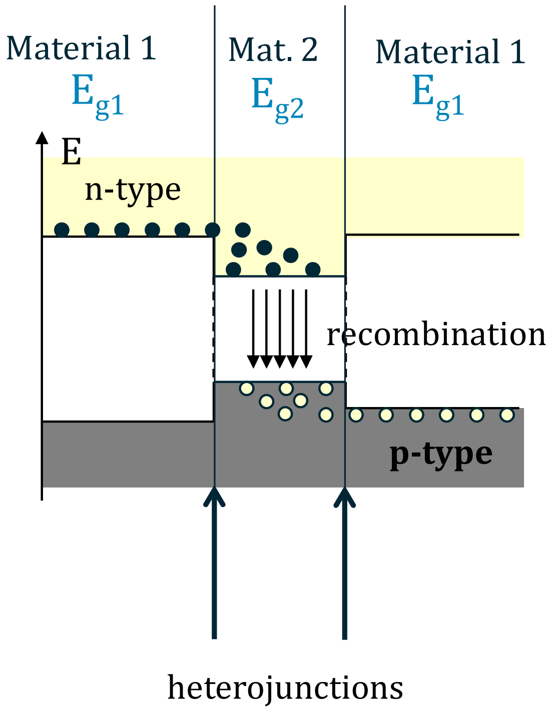
- Heterojunction: two different materials => different bandgap $E_{g1} > E_{g2}$
  - Current carried by electrons on n-side
    by holes on the p-side
    holes are stopped at pn-junction by potential barrier
    electrons are injected into the p region
  - Recombination on the side with the smallest bandgap
  - Light not absorbed on n-side
  - Light generated in doped material (absorption) over diffusion length



Double heterojunction – carrier confinement

- Heterojunction:
  two different materials => different bandgap $E_{g1} > E_{g2}$

- Double heterojunction pin-structure:
  - middle layer has smallest bandgap
  - middle layer is undoped – intrinsic material
    – thin (e.g. 100nm)
  - Holes injected into middle layer from p-doped layer
  - Electrons injected into middle layer from n-doped layer
    => high concentration of excess carriers
  - Electrons and holes captured in potential well in Material 2
  - Recombination, light generation in thin middle layer
    that is undoped (intrinsic)
  - Doped layers are transparent to light generated in middle layer.



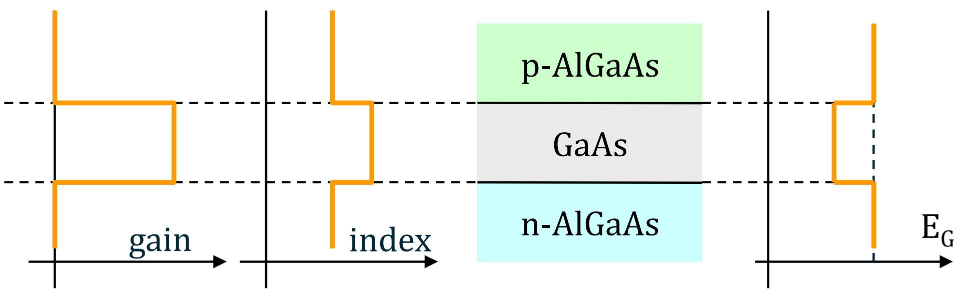
Double heterostructure – waveguiding

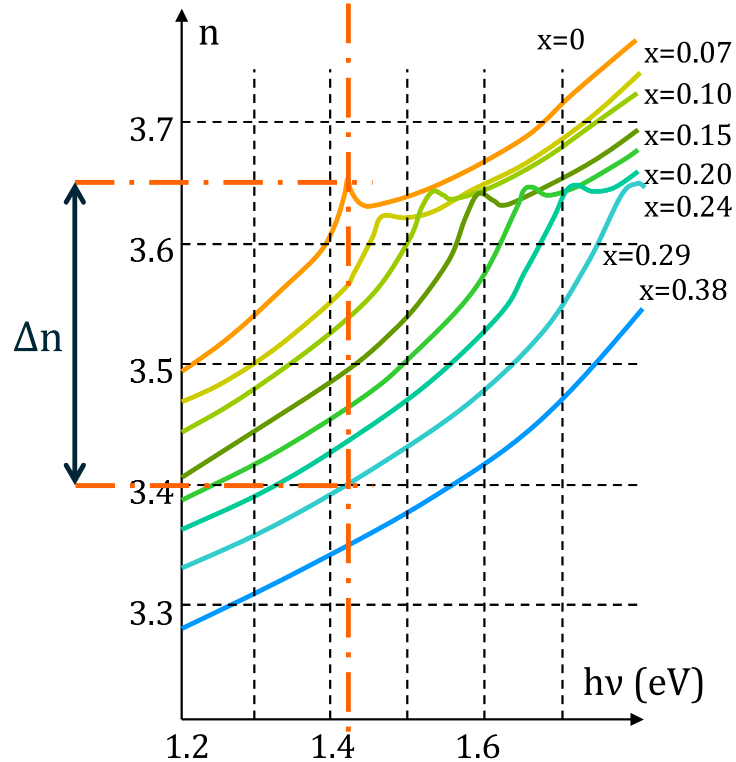
- Heterojunction:
  two different materials => different bandgap $E_{g1} > E_{g2}$

- Material with higher band gap -> lower refractive index -> Heterojunction structure forms a waveguide!

  Example GaAs – $Al_xGa_{1-x}As$

  E_g GaAs = 1.424 eV => λ = 871 nm



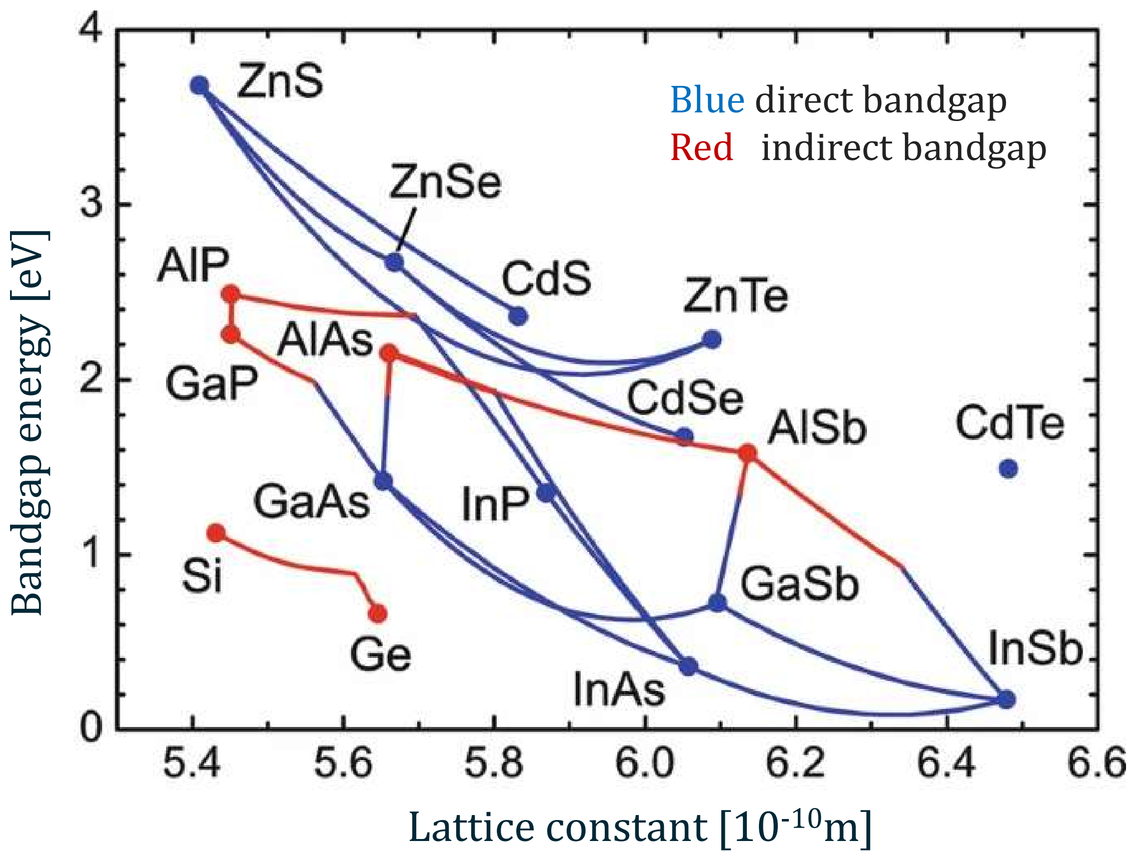


$Al_xGa_{1-x}As$

Semiconductor materials for heterojunctions

Materials with different bandgap stacked
->
<u>same lattice constant required</u> for growth of single crystalline materials

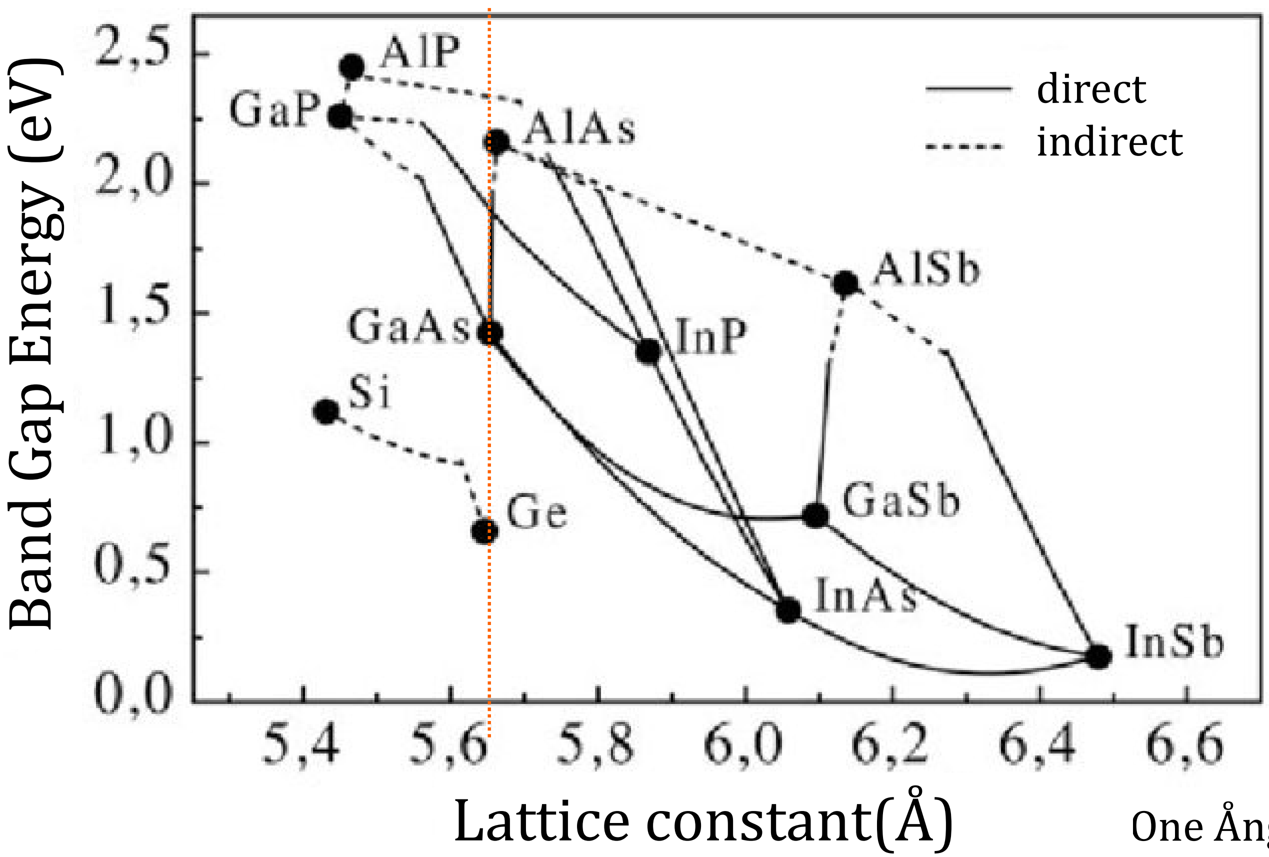
Materials growth is started
from primary or binary semiconductors



Böer, K.W., Pohl, U.W. (2023). Bands and Bandgaps in Solids. In: Semiconductor Physics. Springer, Cham. https://doi.org/10.1007/978-3-031-18286-0_8

GaAs–AlGaAs

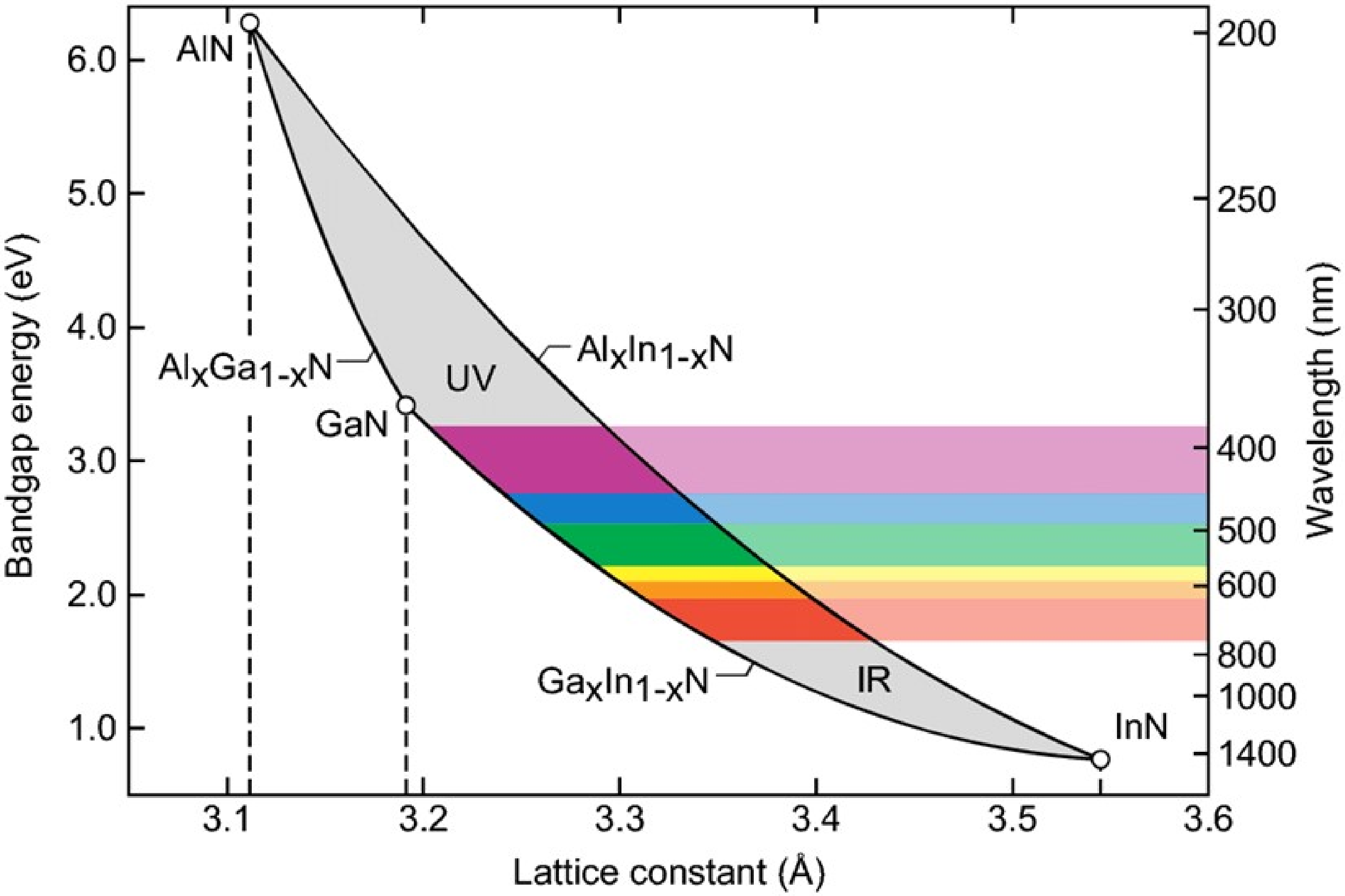
(5) (PDF) III-V compounds for solar cell applications (researchgate.net)



- Lattice constant GaAs – AlGaAs only 0.12% difference
- Material $Al_xGa_{1-x}As$ has direct bandgap for $0 < x < 0.45$
- Important for 870 – 720nm e.g. pump diodes at 808 nm

One Ångstrom (Å) = 10^{-10} meter

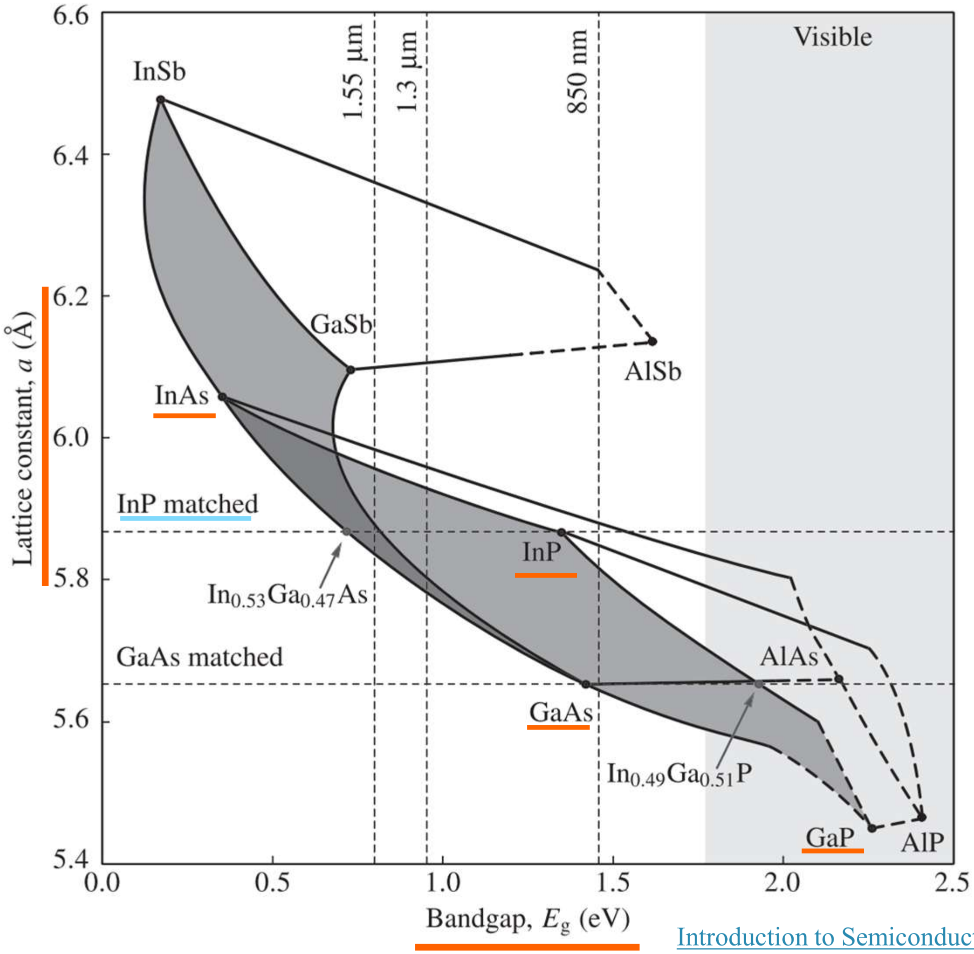
GaN–AlN–InN



(Extracted from E. F. Schubert, Light-Emitting Diodes. Cambridge University Press, 2006).

- Quarternary semiconductors cover surface in diagram
- Material system GaN – $Ga_xIn_{1-x}N$ for solid state lighting
- Most efficient for 400-390 nm

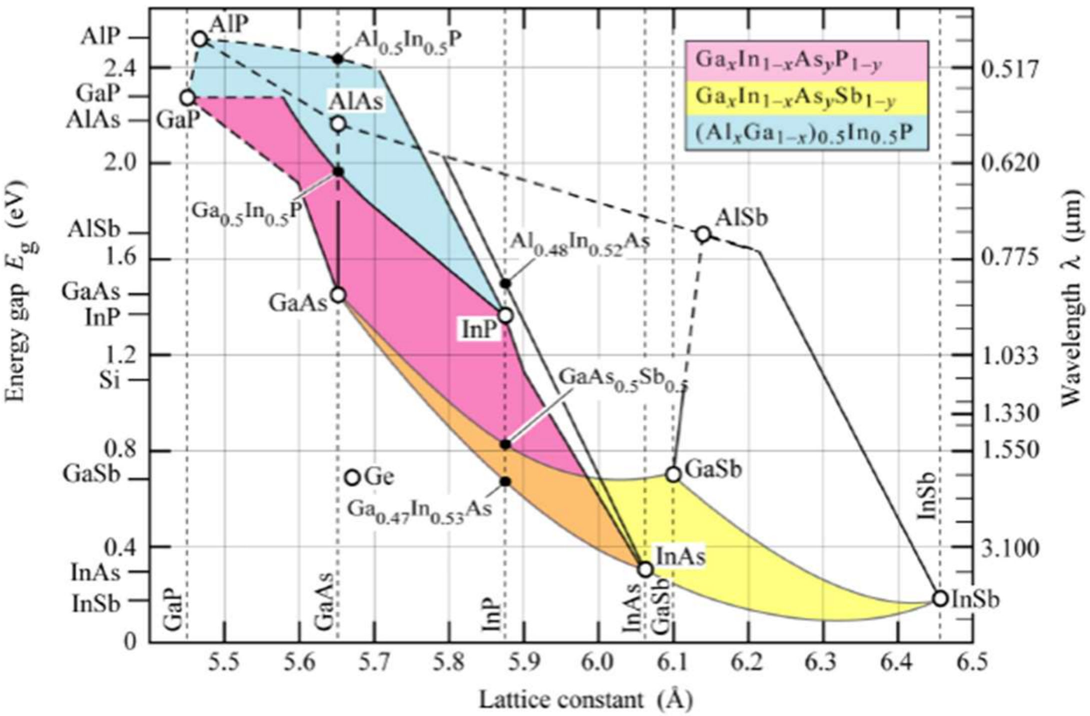
InP – $In_{1-x}Ga_xAs_{1-y}P_{1-y}$



[Introduction to Semiconductors – Fosco Connect (fiberoptics4sale.com)](fiberoptics4sale.com)

- Quarternary semiconductors cover surface in diagram
- Notice X and Y axis exchanged
- Material system InP - $In_{1-x}Ga_xAs_{1-y}P_{1-y}$ for tele and data communication
- Wavelengths from 1200 – 1640 nm can be realized lattice matched to InP

GaSb – $Ga_xIn_{1-x}As_ySb_{1-y}$



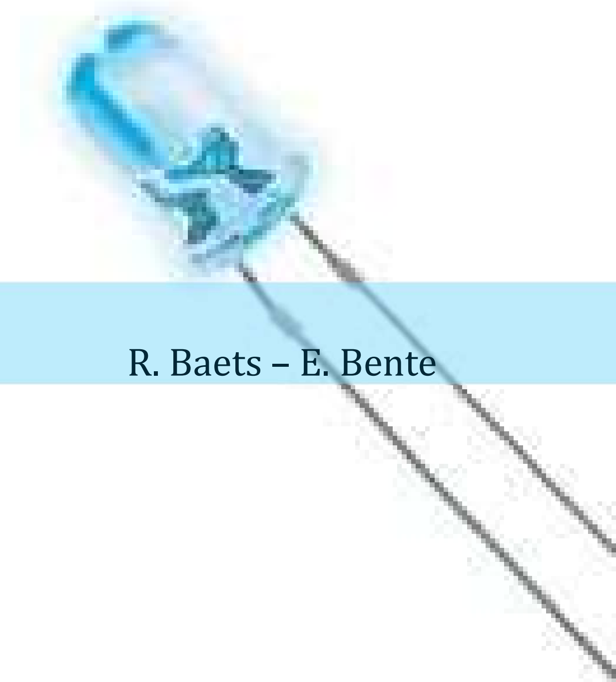
[Origin: Chegg.com]

- Quarternary semiconductors cover surface in diagram
- System GaSb - $Ga_xIn_{1-x}As_ySb_{1-y}$ for gas detection – remote sensing
- Wavelengths from 2000 – 3000 nm can be realized lattice matched to GaSb
  - Sb = Antimony

Next: semiconductor-based devices

Photonics

R. Baets – E. Bente



Semiconductor light sources - Part C

LED’s

Semiconductor light sources

- LEDs
  - Lighting
  - Displays
  - Short range communication (fibre – free space (LiFi)

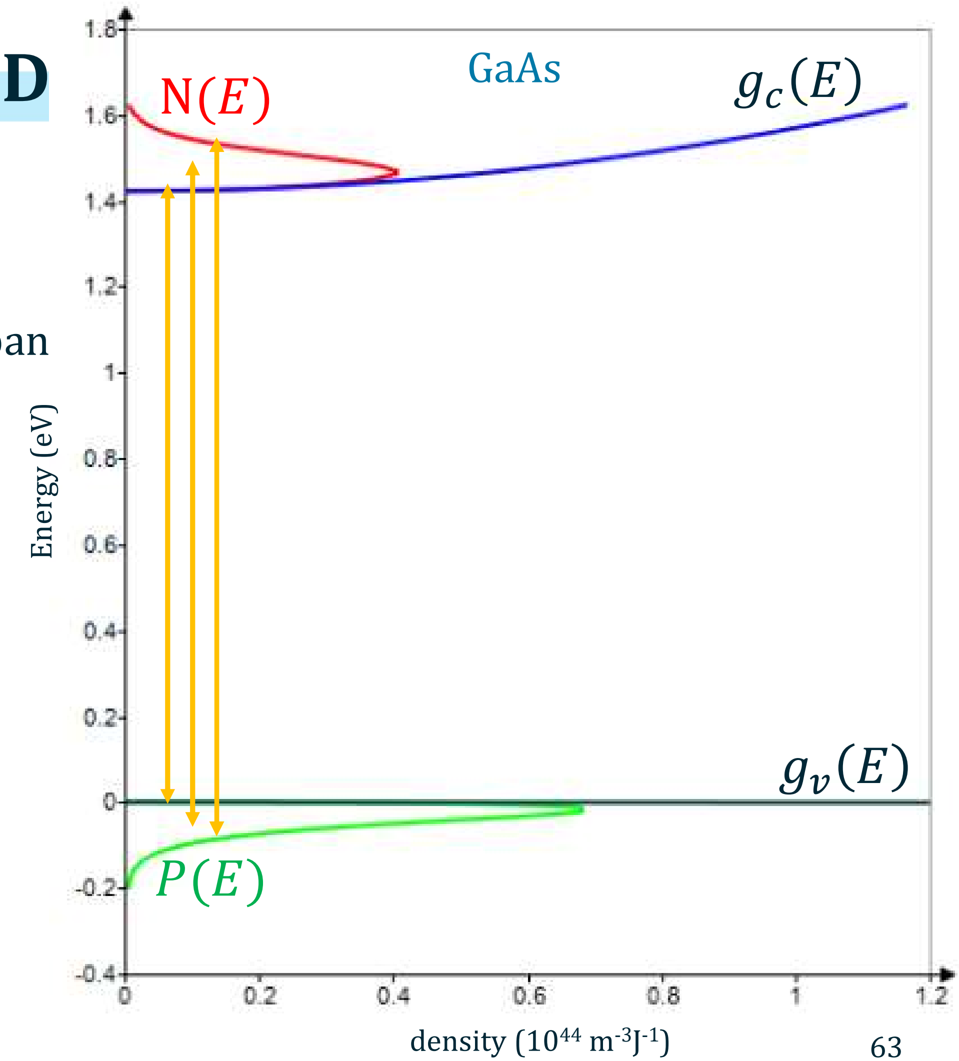
- Laser diodes
  - Pump laser (e.g. for TiSa laser, fibre laser)
  - BluRay-player, PC-mouse, supermarket checkout
  - Optical communications – fibre - free space
  - LIDAR
  - Medical applications
  - Lighting
  - Manufacturing (e.g. soldering)

Radiative recombination in LED

- light emission: photon energy ~ just over bandgap
  => color depends on material composition
  => spontaneous emission – spectrally wide,
  determined by distribution of carriers over the ban
- Internal efficiency η_i
  - Fraction of electron hole pairs that recombine to produce a photon – material crystal quality
  - Can be close to 100% for infrared LEDs
  - Efficiency cab decrease at shorter wavelengths (green, blue)
    GaN blue LED can achieve 90%

$GaAs_{1-x}P_x$ → IR, red to green

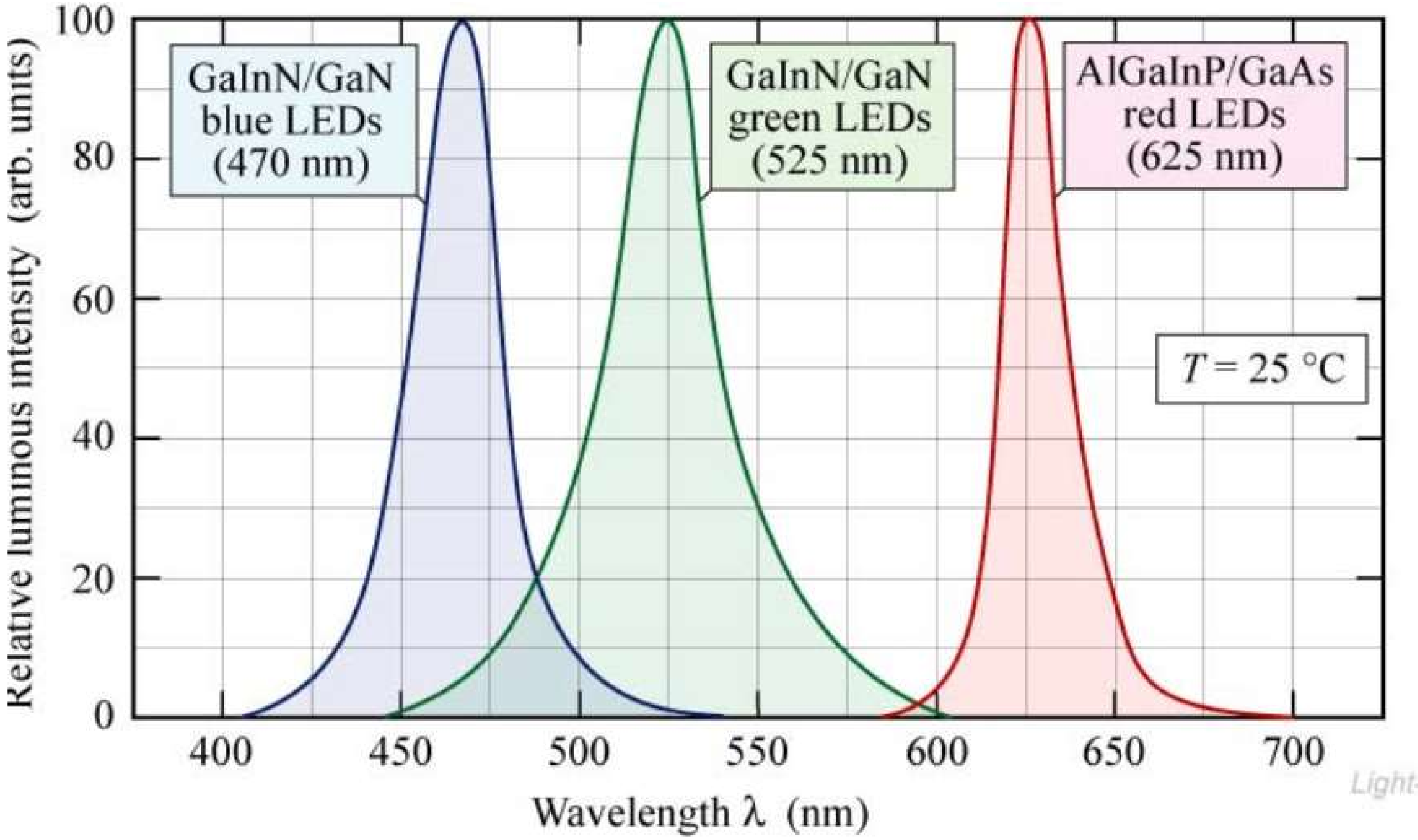
Nitrides → green to blue, UV



LED-materials

λ (nm)	Color	Material	Application
1000-1600	IR	$In_xGa_{1-x}As_yP_{1-y}$	fiber communication
850-900	IR	GaAs	remote control
650	red	$GaAs_{60}P_{40}$, InGaP	displays
620	orange	$GaAs_{35}P_{65}$:N, InAlGaP	displays
590	yellow	$GaAs_{15}P_{85}$:N	displays
570	green	GaP:N	displays
280-500	Blue/UV	InGaN	lighting – displays

Typical LED output spectra



After Toyoda Gosei Corp., 2000 (rpi.edu)

Internal quantum efficiency

- Definition η_i : the number of emitted photons per e-h pair
  U_r e-h recombination rate per unit volume for radiative recombination
  U total e-h recombination rate per unit volume

$$\eta_i = \frac{U_r}{U} = \frac{1/\tau_r}{1/\tau}$$

τ_r = Radiative carrier lifetime

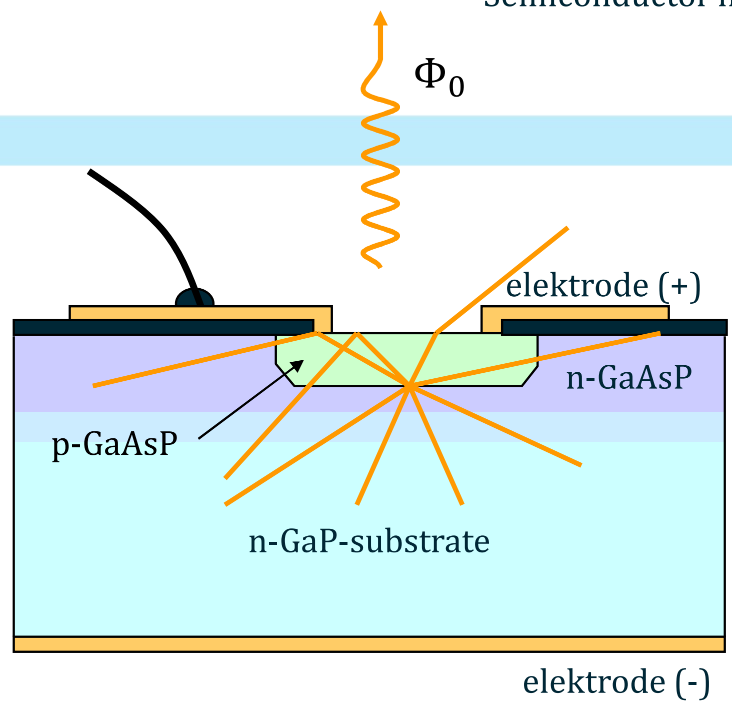
τ = Carrier lifetime

- Photon flux Φ_i generated in volume V in which e-h recombine

$$\Phi_i = U_r V \quad \Rightarrow \quad \Phi_i = \eta_i G V$$

  - G: electron-hole generation per time- and volume unit
    → Current injection I : $G = I/(e \cdot V)$
  - steady state situation: total recombination rate = injection rate $G = U$

Extraction efficiency (1)



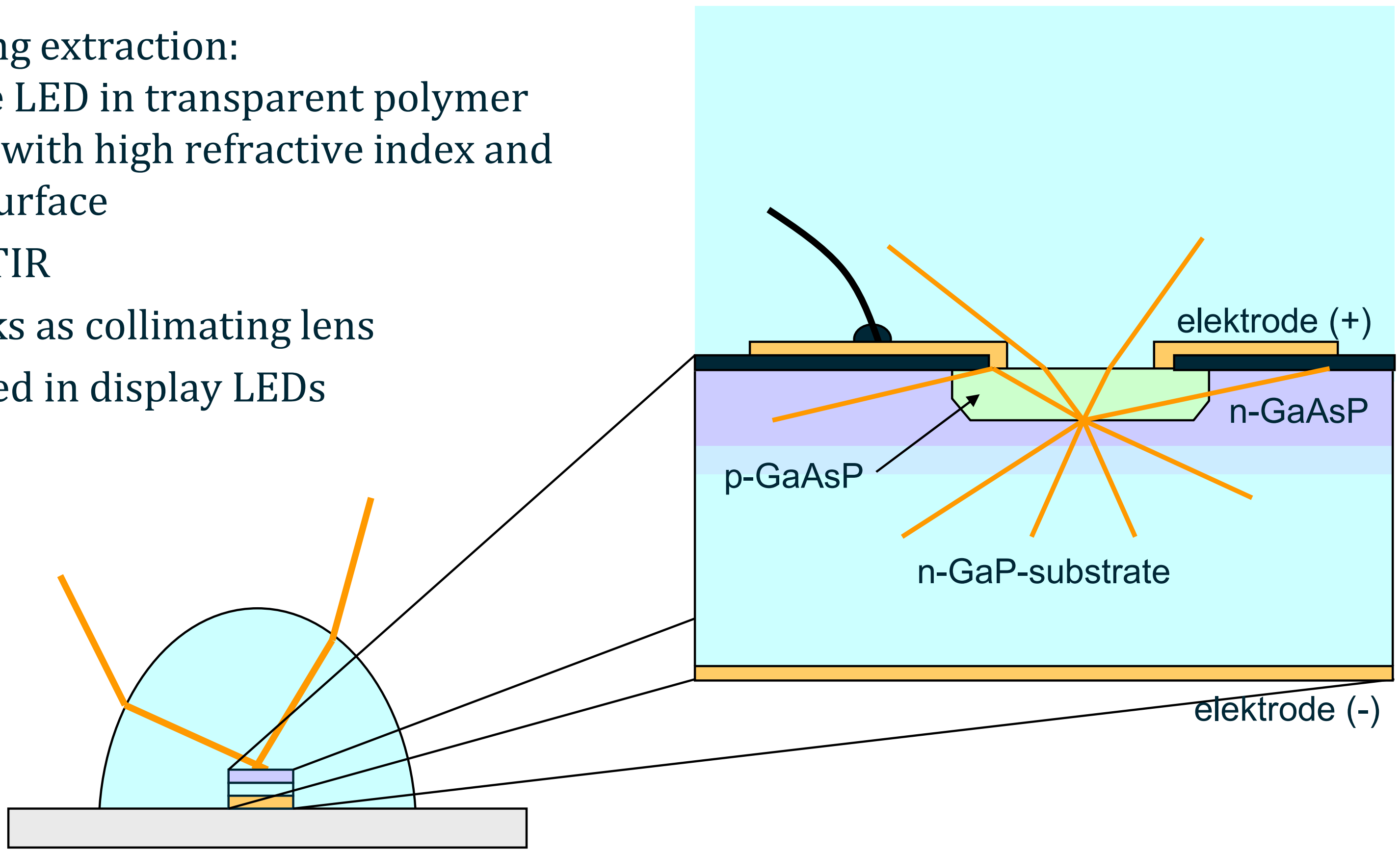
- Extraction efficiency η_e
  - emission to substrate
  - total internal reflection
  - reflection on top-electrode
  - mostly < 1%
- Lambertian emitter:
  - isotropic radiation in LED
  - strong refraction on a flat surface
- External quantum-efficiency η_{ex}
  = ratio between number of photons leaving the LED and number of injected electrons

$$\eta_{ex} = \eta_e \eta_i \qquad \Phi_0 = \eta_e \Phi_i = \eta_e \eta_i \frac{I}{e} = \eta_{ex} \frac{I}{e}$$

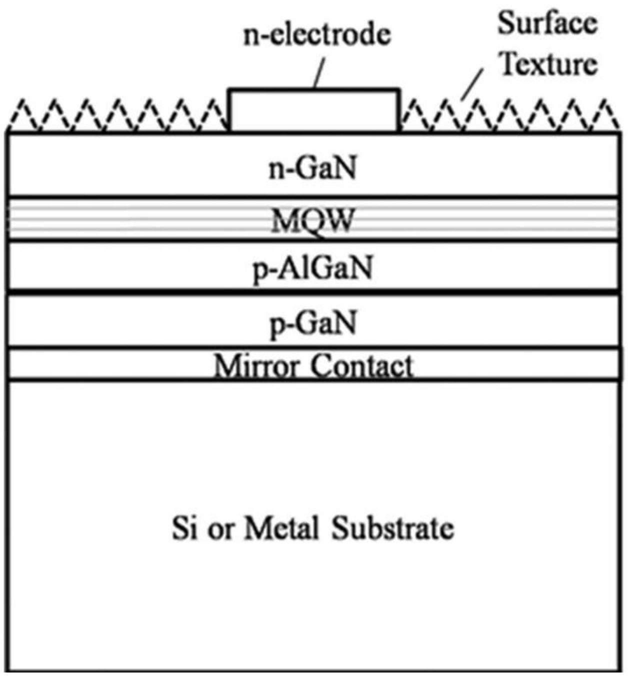
with I the current through the pn junction
Φ_0 the number of photons per second emitted

Extraction efficiency (2)

- Improving extraction:
  integrate LED in transparent polymer material with high refractive index and curved surface
  - less TIR
  - Works as collimating lens
- Often used in display LEDs



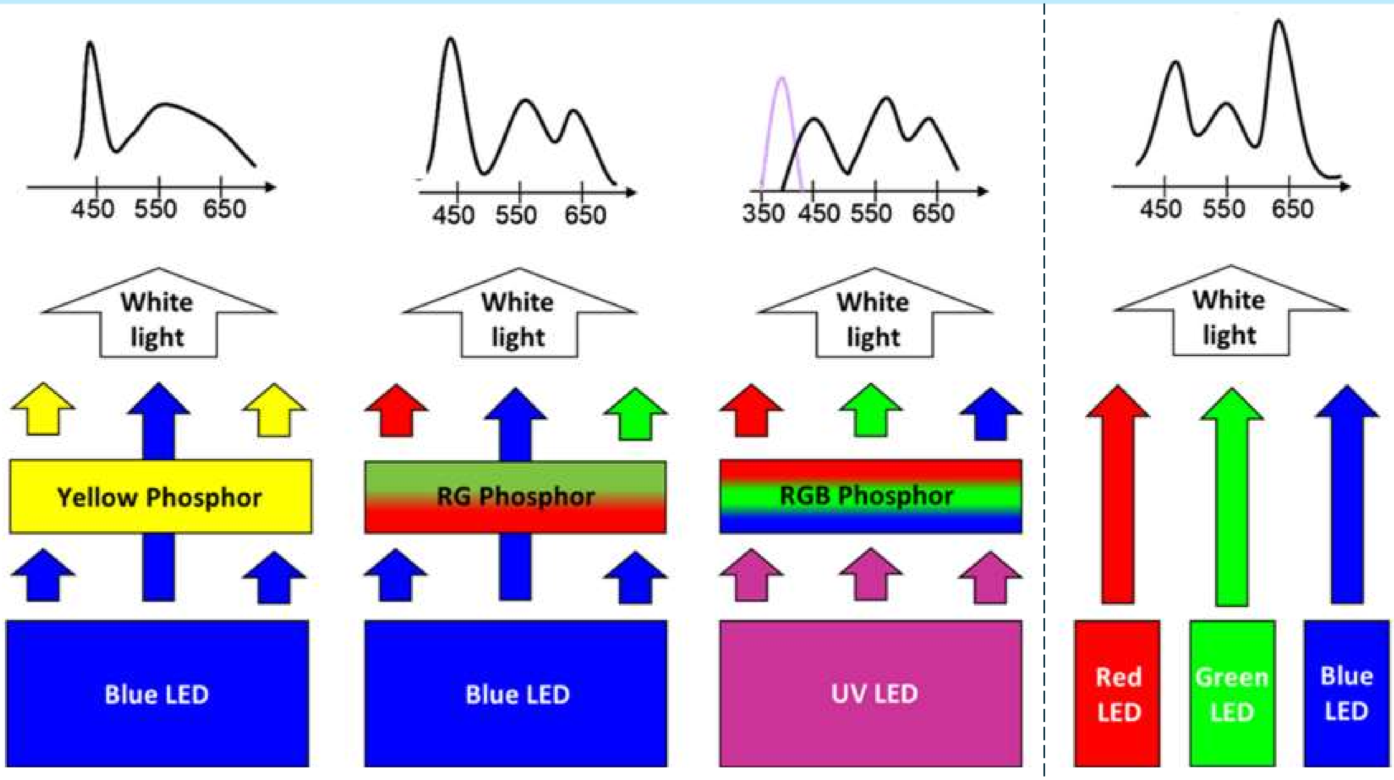
Thin GaN LED structure



From: Optical Design for LED Solid-State Lighting A guide
Ching-Cherng Sun and Tsung-Xian Lee

- Substrate can be sapphire (Al_2O_3), SiC Special techniques are applied to deal with lattice mismatch (16% for Al_2O_3).
- LED can be bonded to silicon or metal substrate for good thermal and electrical conductivity
- Surface texture to reduce TIR effects
- Fluorescent phosphor can be applied to top change colour of light

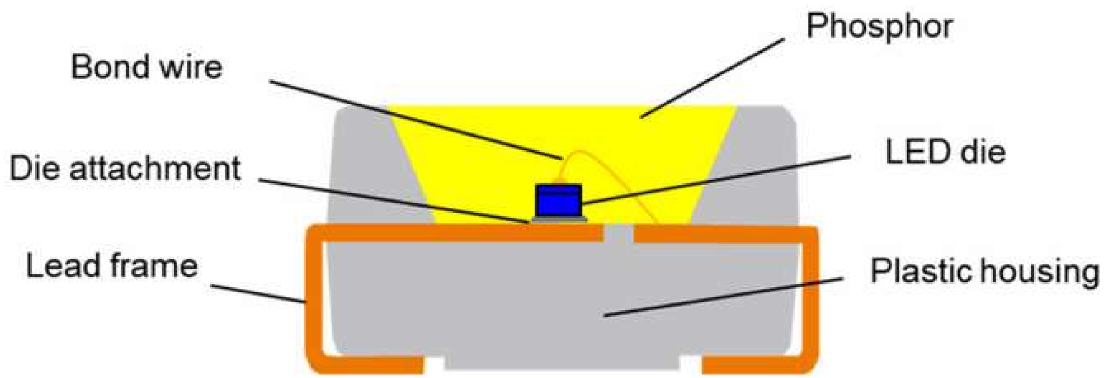
Ways to generate white light



From: Optical Design for LED Solid-State Lighting A guide Ching-Cherng Sun and Tsung-Xian Lee

- Phosphor on top of LED – inorganic photoluminescent material (fluorescence – excitation blue / UV - emission longer wavelengths)

Mid-power SMD LED

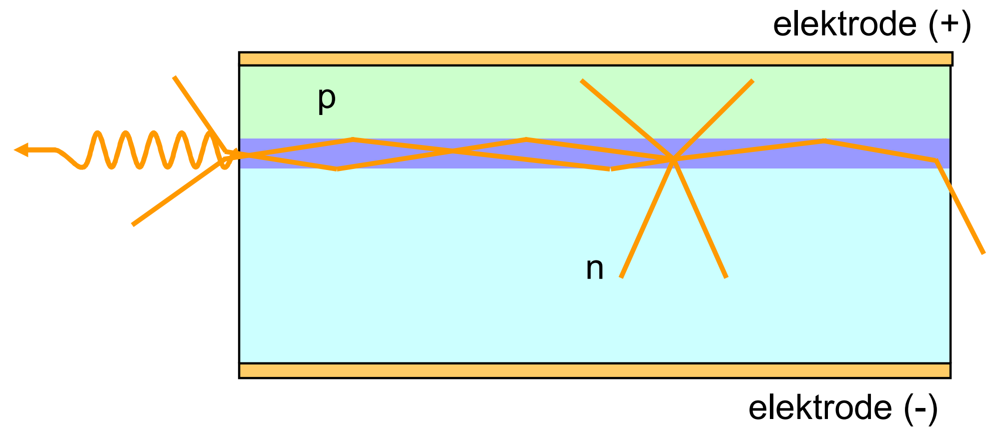


Sideways emitting LED

- LED in waveguide structure: part of the light is guided by waveguide
- Light has a long path though active, light generating material – must be above transparency
- There can be no cavity (as with laser diodes): mirror effect of facets needs to be suppressed
- Much larger radiance:
  - Same extraction efficiency
  - Small radiating surface
- Superluminescent operation high current

  =>Stimulated emission is important

  => Amplification of spontaneously emitted light
  - narrower spectrum
  - higher efficiency



LED Modulation bandwidth

- Transfer of current variation to light variation (Response)

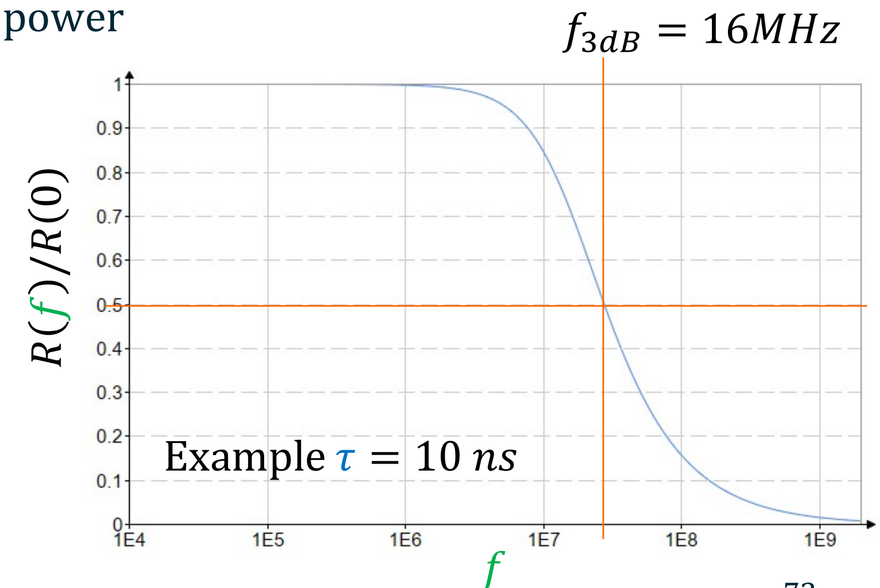
$$R(f) = \frac{\Delta P}{\Delta I} = \frac{R(0)}{\sqrt{1 + 4\pi^2 f^2 \tau^2}}$$

with ΔI the modulation amplitude of the electrical current (sinusoidal at frequency f)
and ΔP the amplitude of the modulation of the optical power

- electrical 3 dB bandwidth

$$R(f_{3dB}) = \sqrt{0.5} \qquad f_{3dB} = \frac{1}{2\pi\tau}$$

- with τ the lifetime of the carriers:
  In semiconductors: $\tau \sim$ ns => f_{3dB} = 50 - 100 MHz
- In practice often the capacity of the LED also limits the bandwidth



LEDs vs. laserdiodes

- LEDs

  - Low radiance
  - Low modulation bandwidth
  - Broad spectrum (sometimes that is good)

  \+ cheaper
  \+ reliable (up to 100,000h lifetime)
  \+ efficiency and size compared to other lighting technology
  \+ good in applications where low time coherence is important (no speckle)

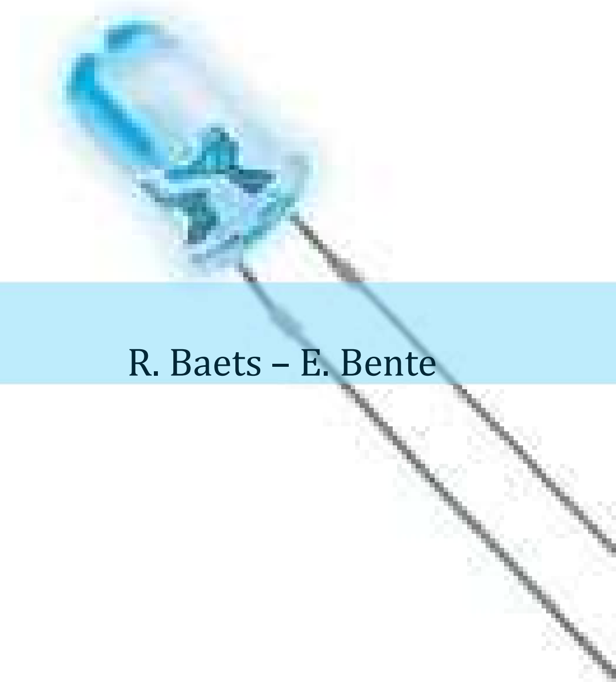
Excercise: LED

- consider a double hetero junction LED n-InP/InGaAs/p-InP with the following properties:

- bandgap InP: 1.3 eV InGaAs: 0.8 eV
- radiative carrier lifetime τ=1.20 ns
- Area 1x1mm^2
- Recombination takes place in the 100nm thick InGaAs layer
- extraction efficiency η_e=0.05, internal efficiency η_i=0.25

- What is the emission wavelength λ_0 (vacuum wavelength) ?
- What is the 3db bandwidth f_{3db}?
- What is the radiant excitance M^e of the LED at 100mA current?

Photonics



R. Baets – E. Bente

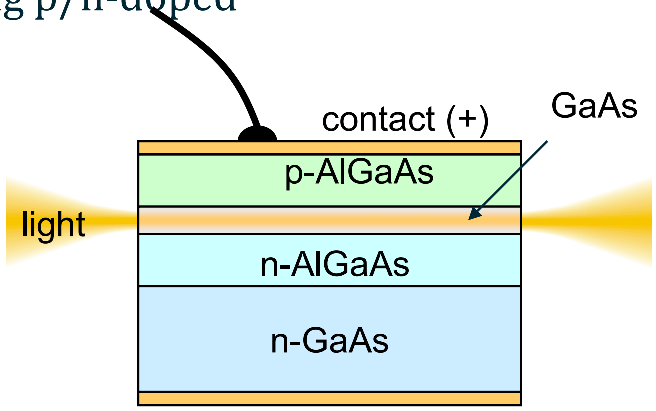
Semiconductor light sources – Part D

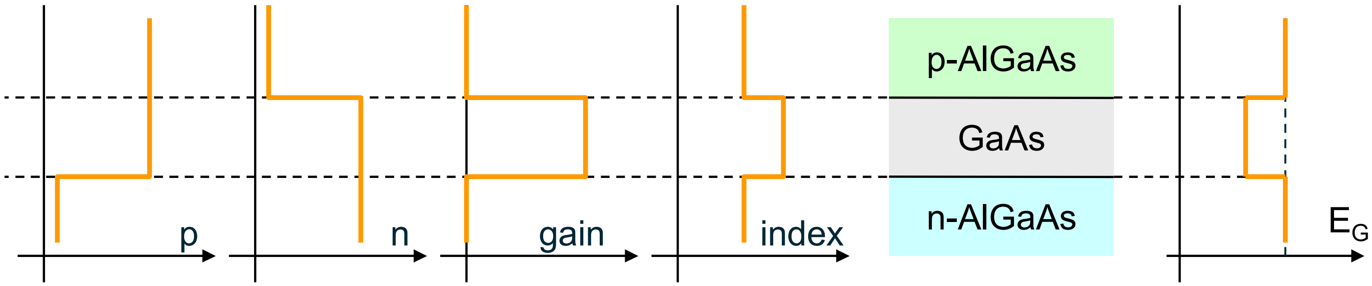
Laser diodes

Double heterojunction-laser – example GaAs-AlGaAs

- Thin active GaAs layer (0.2 µm) intrinsic material; cladding p/n-doped
- Active layer:
  - higher refractive index → optical confinement
  - lower E_{gap} → charge confinement
  - high population inversion at optical mode position
- Resonator
  - Cleaved facets at ends act as mirrors
  - Light in waveguide

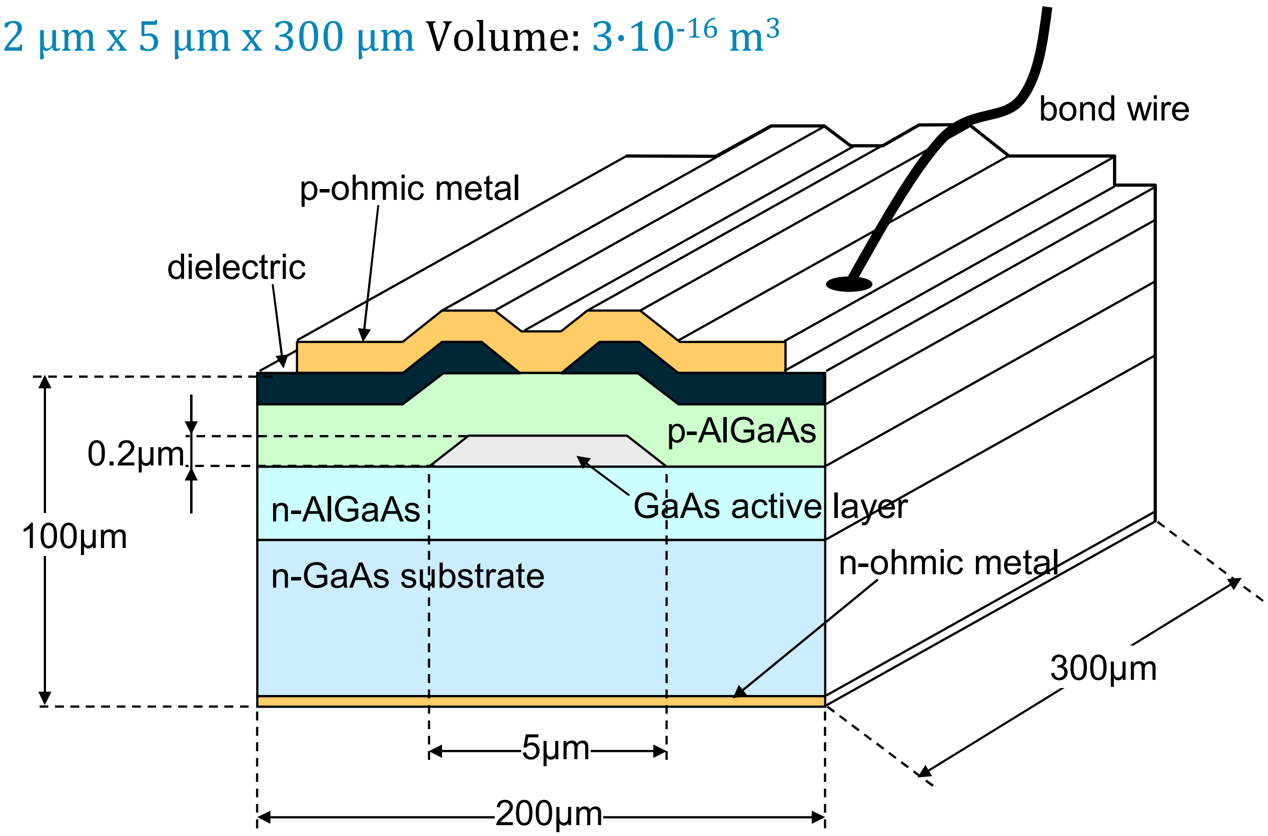
→ Typical current density for transparency (500 A/cm²)



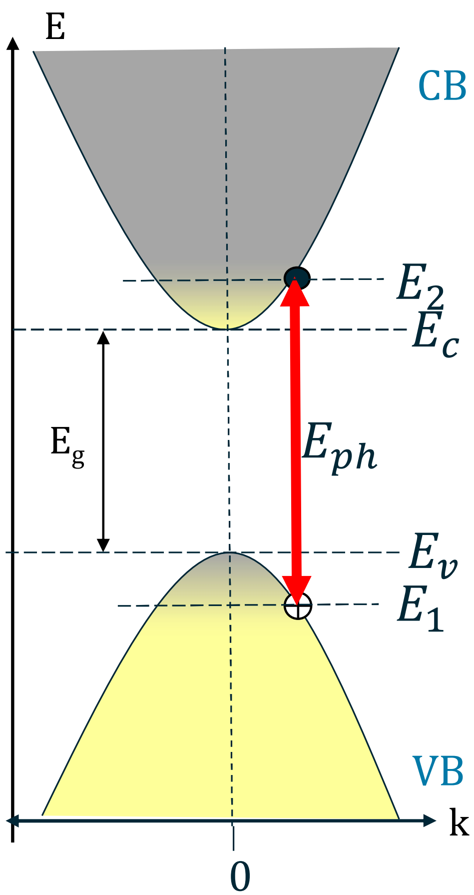


Double heterojunction-laser – example GaAs-AlGaAs

- threshold= 10-20 mA
- active medium = 0.2 µm x 5 µm x 300 µm Volume: $3\cdot10^{-16}$ m^3



Example – current for transparency in GaAs laser (1)



Estimate current: GaAs transparent for light at $\lambda = 835\ nm$.

GaAs semiconductor material (intrinsic)

Bandgap: $E_g = 1.42\ eV \rightarrow \lambda_g = 873\ nm$

Bottom CB: $E_c = 1.42\ eV$

Top VB: $E_v = 0.0\ eV$ $T = 300\ K$

Condition gain: $E_{Fn} - E_{Fp} \geq E_{ph}$

Transparency at: $E_{Fn} - E_{Fp} = E_{ph} = E_2 - E_1$

Calculate (excess) carrier concentration for transparency:
Find E_{Fn} and $E_{Fp} = E_{Fn} - E_{ph}$ such that:

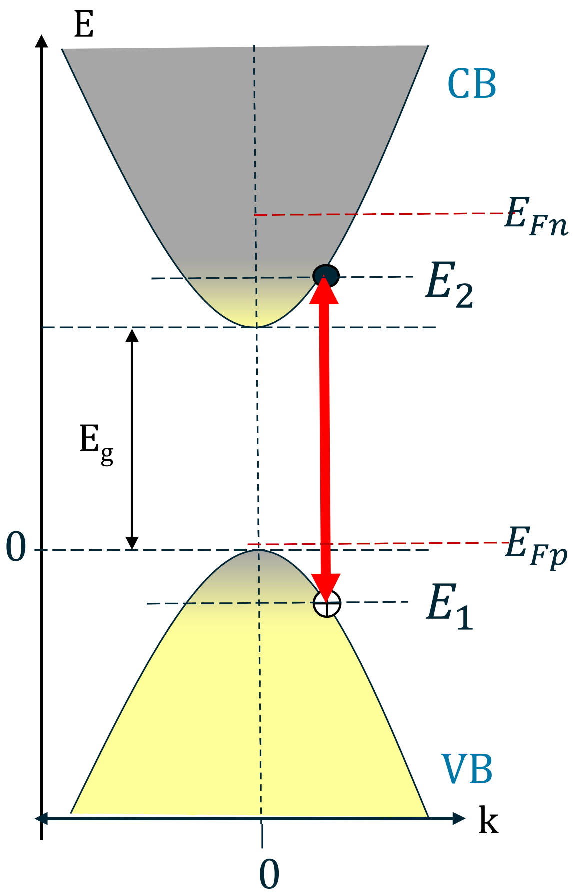
$$\delta n = \int_{E_c}^{\infty} f_c(E) \cdot g_c(E) \cdot dE = \delta p = \int_{-\infty}^{E_c} \left(1 - f_v(E)\right) \cdot g_v(E) \cdot dE$$

Calculation numerical for exact solution

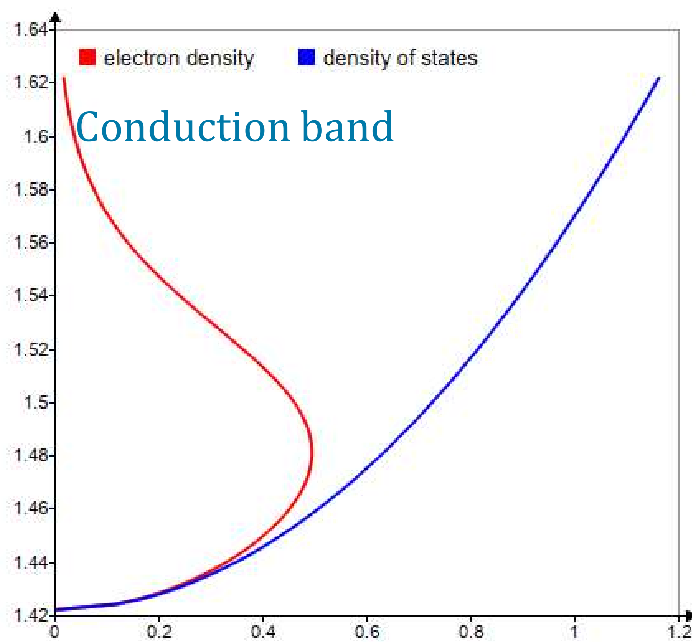
Using approximations analytical solution possible.

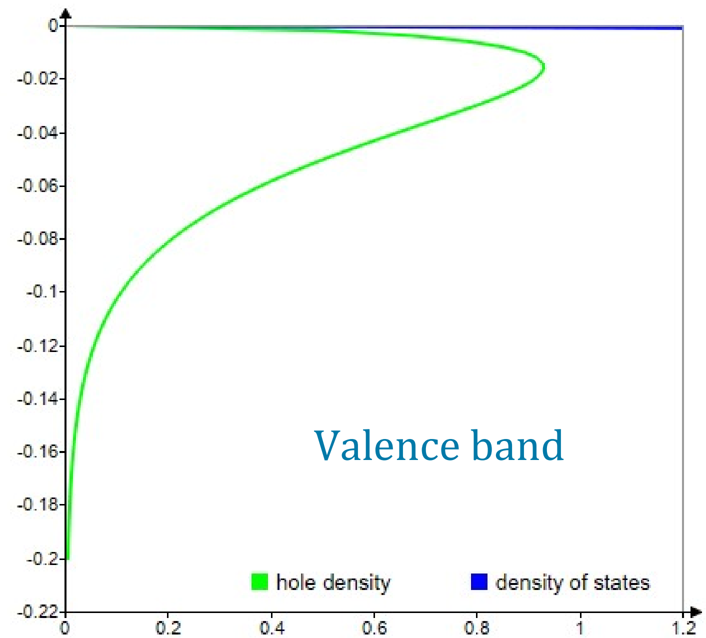
Example – current for transparency in GaAs laser (2)

Solution for is $E_{Fn} = E_g + 0.09236\ eV = 1.51236\ eV$ => $E_{Fp} = E_{Fn} - E_{ph} = 0.02752\ eV$



$$\delta p = \delta n = 8.53 \cdot 10^{23}\ m^{-3}$$





Example – current for transparency in GaAs laser (3)

Excess carrier concentration in GaAs semiconductor material (intrinsic) needed for transparency: $\delta p = \delta n = 8.53 \cdot 10^{23}\ m^{-3}$

If carrier lifetime is : $\tau = 5 \cdot 10^{-9}$s (usually this is not known accurately)

In steady state: $\frac{\delta n}{\tau} = 1.71 \cdot 10^{32}\ m^{-3} s^{-1}$ Injected carriers needed to reach $\delta p = \delta n$

Injected current: $I_T = \frac{\delta n}{\tau} \cdot Volume \cdot e = 8.2\ mA$ Volume= 0.2 µm x 5 µm x 300 µm = $3 \cdot 10^{-16}\ m^3$

Current density needed for transparency:

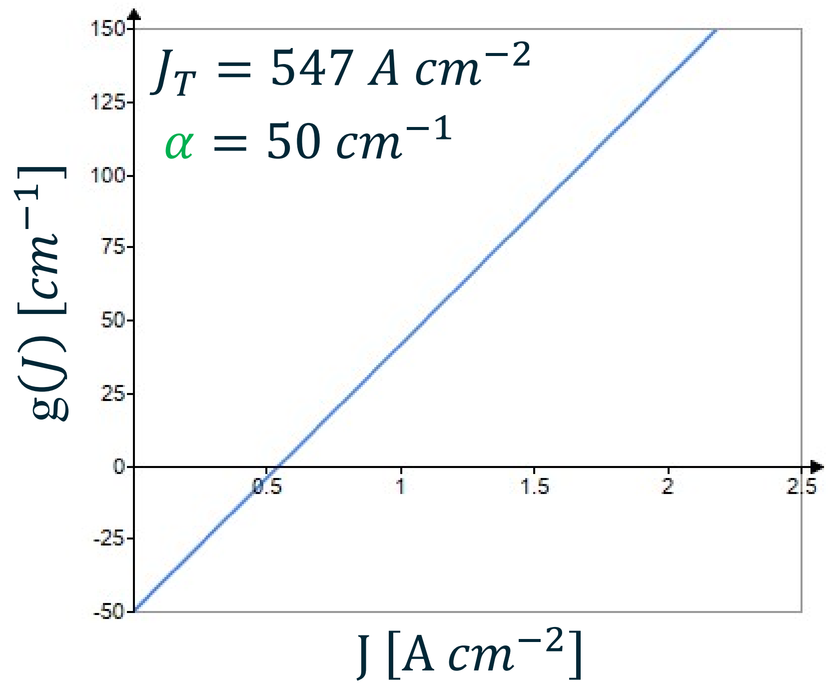
$$J_T = \frac{I_T}{l_{GaAs} \cdot w_{GaAs}} \cdot Volume \cdot e = 547 \frac{A}{cm^2}$$

Amplification

- Simple phenomenological expression for amplification g(J) at peak gain wavelength λ_p as a function of electrical injection current density

$$g(J) = \alpha\left(\frac{J}{J_T} - 1\right)$$

- J = injected current density
- J_T = transparency current density
- α = absorption without injection



Lasing condition

- Mirrors: facets cleaved along crystal planes
- Reflectivity value $$R = \left(\frac{n-1}{n+1}\right)^2$$ e.g. GaAs (n=3.6) => R=0.32
- Gain compensates resonator losses
  - Light scattering loss in the amplifier: α_s loss per unit length
  - Transmission of the cleaved facets (mirror reflectivities R_1, R_2)
- Threshold condition gain: $$g_{th} = \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right) + \alpha_S$$ See exercise laser Ch13

define $\alpha_m \equiv \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$ Mirror losses expressed as “loss per unit length”

$$g_{th} = \alpha_r \equiv \alpha_m + \alpha_S$$ all cavity losses: α_r

- Threshold current density: $$g_{th} = \alpha_r = \underset{\substack{\uparrow \\ \text{material absorption}}}{\alpha}\left(\frac{J_{th}}{J_T} - 1\right) \Rightarrow J_{th} = \frac{\alpha_r + \alpha}{\alpha} J_T$$

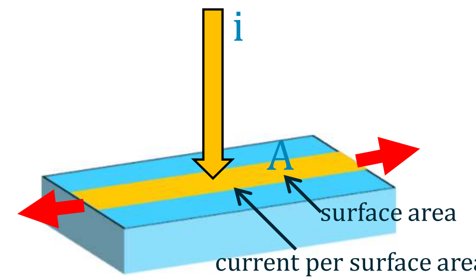
Laser diode characteristics (1)

- Photon flux in the laser Φ with the current $i = J \cdot A$
- $$\Phi = \begin{cases} \eta_{in} \dfrac{i - i_{th}}{e} & i > i_{th} \\ 0 & i < i_{th} \end{cases}$$

$i_{th} = J_{th} \cdot A$

Compare with (13.36)

Internal quantum efficiency η_{in}



- Internal laser power $$P = \eta_{in}(i - i_{th})\frac{h\nu}{e}$$

collecting light
through both mirrors

- Extraction efficiency $$\eta_e = \frac{\alpha_m}{\alpha_m + \alpha_S} = \frac{\alpha_m}{\alpha_r} = \frac{1}{\alpha_r 2L} ln\left(\frac{1}{R_1 R_2}\right)$$

- Emitted power $$P_0 = \eta_d(i - i_{th})\frac{h\nu}{e}$$

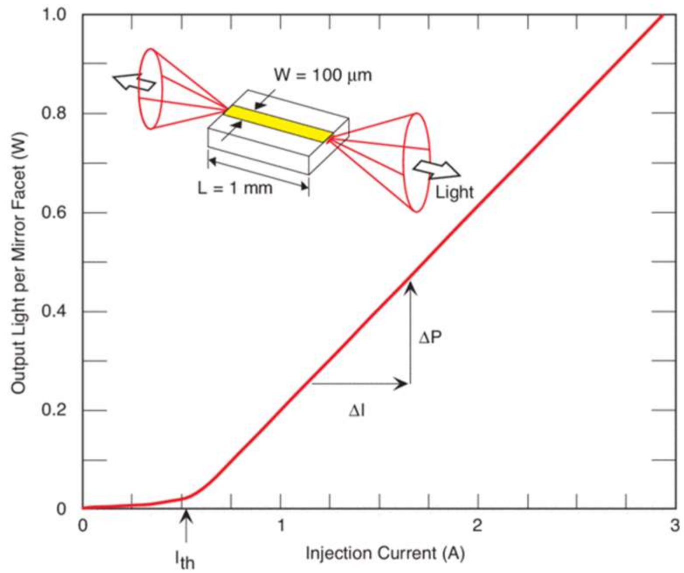
with $\eta_d = \eta_{in}\eta_e$ the external differential quantum efficiency

Laser diode characteristics (2)

- Differential efficiency $$\Re_d = \frac{dP_0}{di} = \eta_d \frac{h\nu}{e}$$

- Global efficiency $$\eta = \frac{P_0}{P_{el}} = \eta_d \left(1 - \frac{i_{th}}{i}\right)\frac{h\nu}{eV}$$ with $$P_{el} = i \cdot V$$

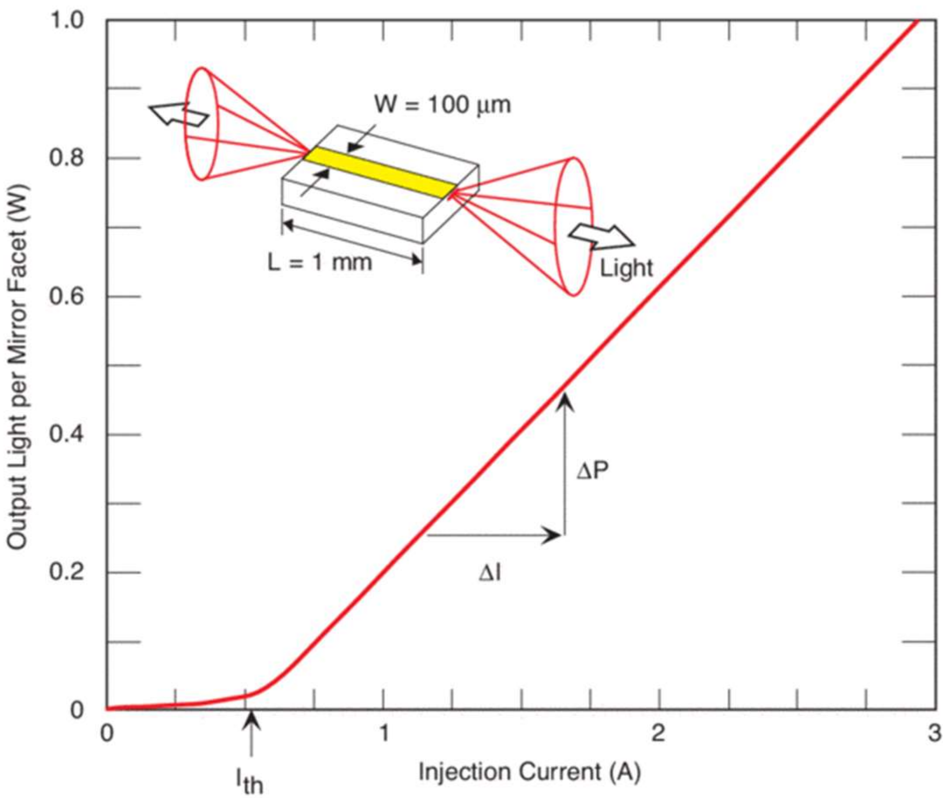
  (optical output power ratio to electrical input power i·V)



Example graph optical output power vs electrical input power.

https://www.newport.com/t/laser-diode-technology

Question



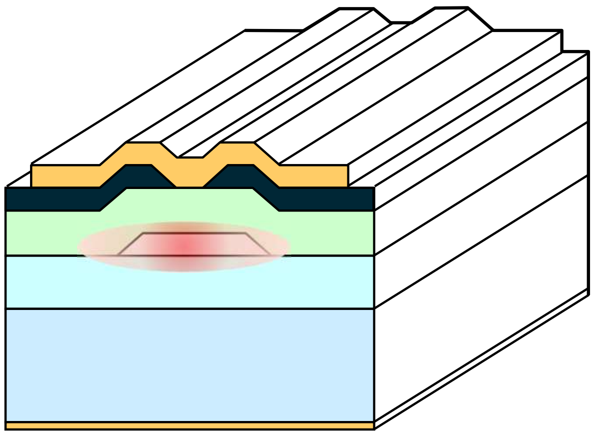
https://www.newport.com/t/laser-diode-technology

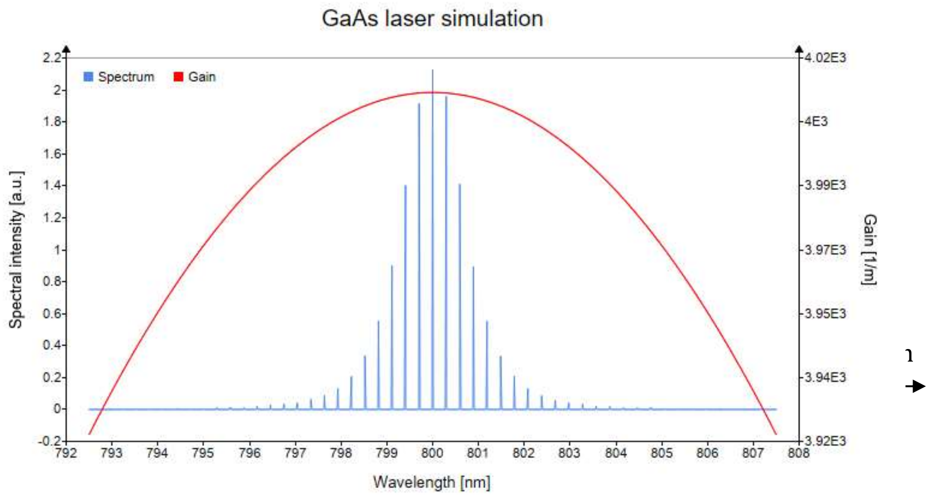
- Assume the data presented are from a GaAs laser
  - Calculate the transparency current and current density for this laser.
  - Comment on the difference between the transparency and threshold current. Discuss possible causes for the difference?

Modes in the DH-laser

- Cavity formed by waveguide
  ➔ no Gaussian beams
  ➔ output beam quality depends on waveguide

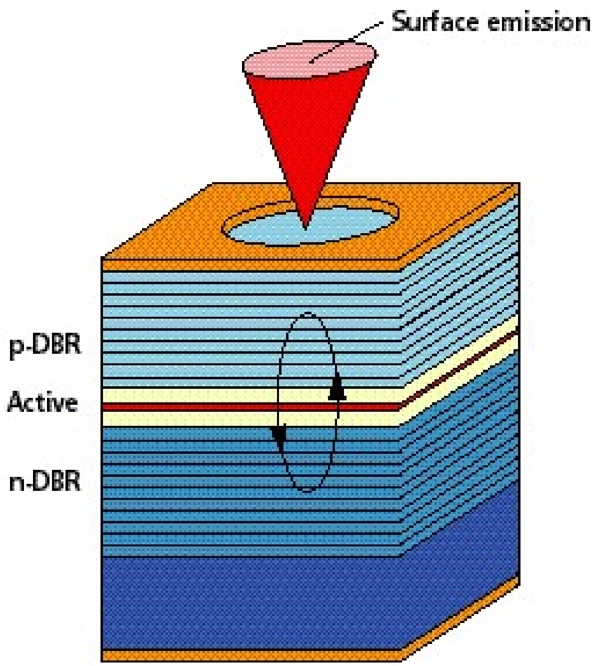
- Lateral-transversal modes:
  Often possible to isolate one mode
  - dimensions → V parameter
  - Index contrast
- Longitudinal modes:
  - short cavity ➔ large mode spacing
  - Band structure ➔ broad gain spectrum
  - ➔ Still multiple modes
  - ➔ use filters / dispersive elements





VCSEL

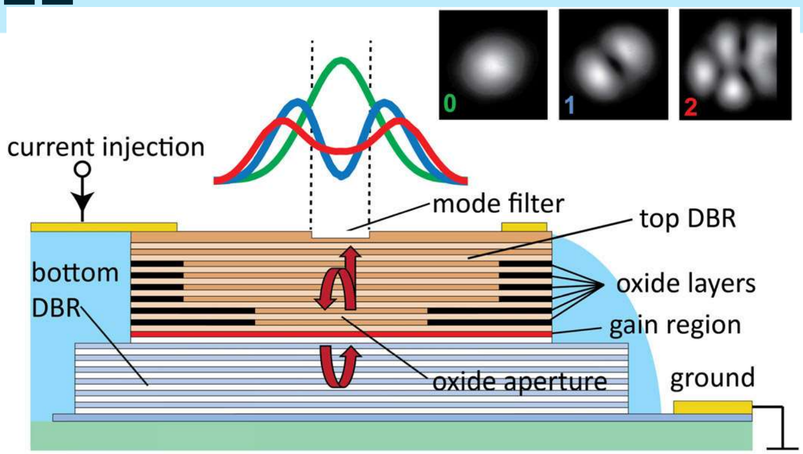
- Vertical cavity surface emitting laser
  - Make the cavity very short-> mode spacing larger than gain bandwidth->only one longitudinal mode is supported.



Guy Verschaffelt VUB Brussel

- Advantages:
  - compact - very short cavity
  - low threshold
  - wafer testable
  - cheaper
  - dense 2D arrays
  - circular light beam - fibre coupling
  - single frequency – low noise
- Difficulties:
  - high reflectivity mirrors
  - series resistance in mirror
  - current flow guiding

VCSEL



http://spie.org/x90452.xml

Top view

Applications

Datacom – 100m distances

Mouse controller

http://www.litrax.com.tw/

Semiconductor lasers vs. other

Semiconductor

- Band structure
- Semiconductor cavity with flat mirrors
- Very small dimensions (<mm)
- Diffraction limited beam, but large divergence angle (good spatial coherence)
- Multiple longitudinal modes (bad temporal coherence)
- Energy consumption to make laser transparent

Gas/Solid-state lasers

- Discrete levels
- Separate spherical mirrors
- Bulky (cm-m)
- Smaller diffraction angle

- Can easily be made single mode
- High power applications (kW)
- High peak power
- Smallest linewidths

Advantages of laser diodes

- Compact (can be packaged as electronic component)
- Simple electrical pumping: low currents / voltages
- Large modulation bandwidth (GHz) (short photon/gain lifetime)
- High efficiency (10%-50%)
- Large gamma of materials: different wavelengths
- Tunable

VCSEL: problem

- VCSEL:
  Vertical Cavity Surface Emitting Laser
  - Semiconductor laser l_0=850nm
  - Gain area: Quantum Wells ($L=2l/n$)
  - Mirror: Distr. Bragg Reflector ($R_{1/2}$=0.999)
  - injection efficiency η_{in}=0.8
  - scattering α_s in MQW area

- Wanted:
  - g_0 for threshold neglecting scattering loss
  - maximum scattering loss α_s in the gain area for an output power of 1mW when pumping 4mA above threshold
  - what is g_0 and max α_s if the front mirror is only reflecting R_1=0.99